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The Proceedings

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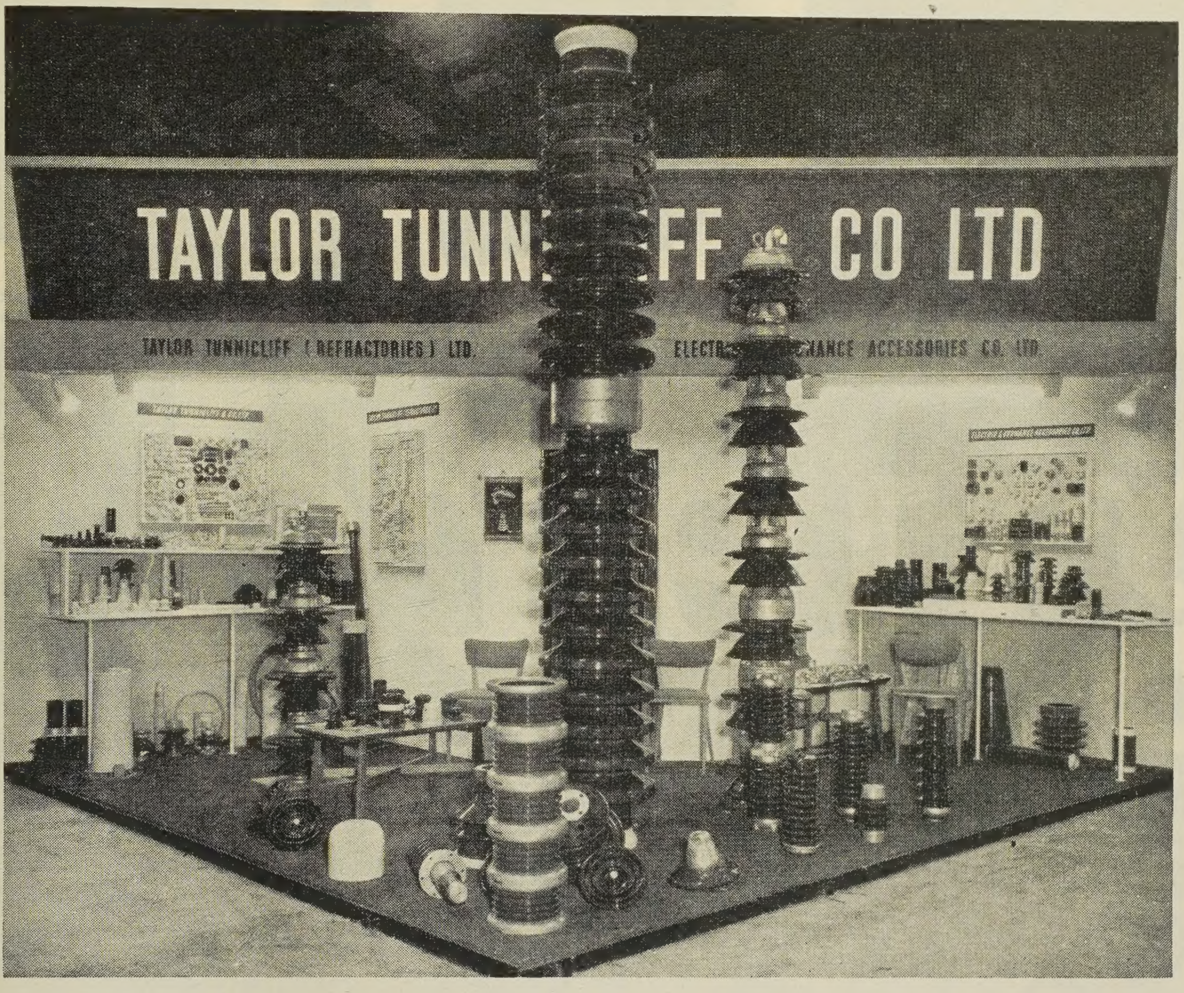

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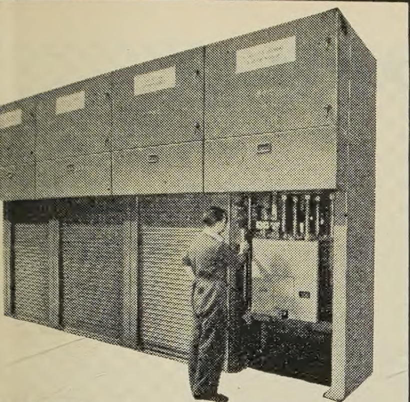

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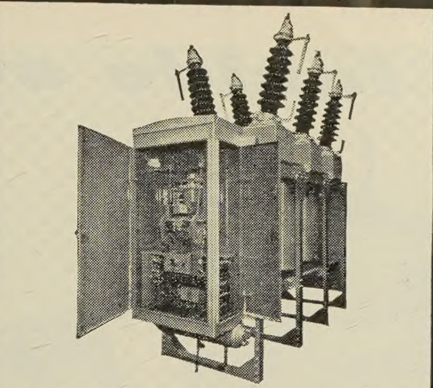

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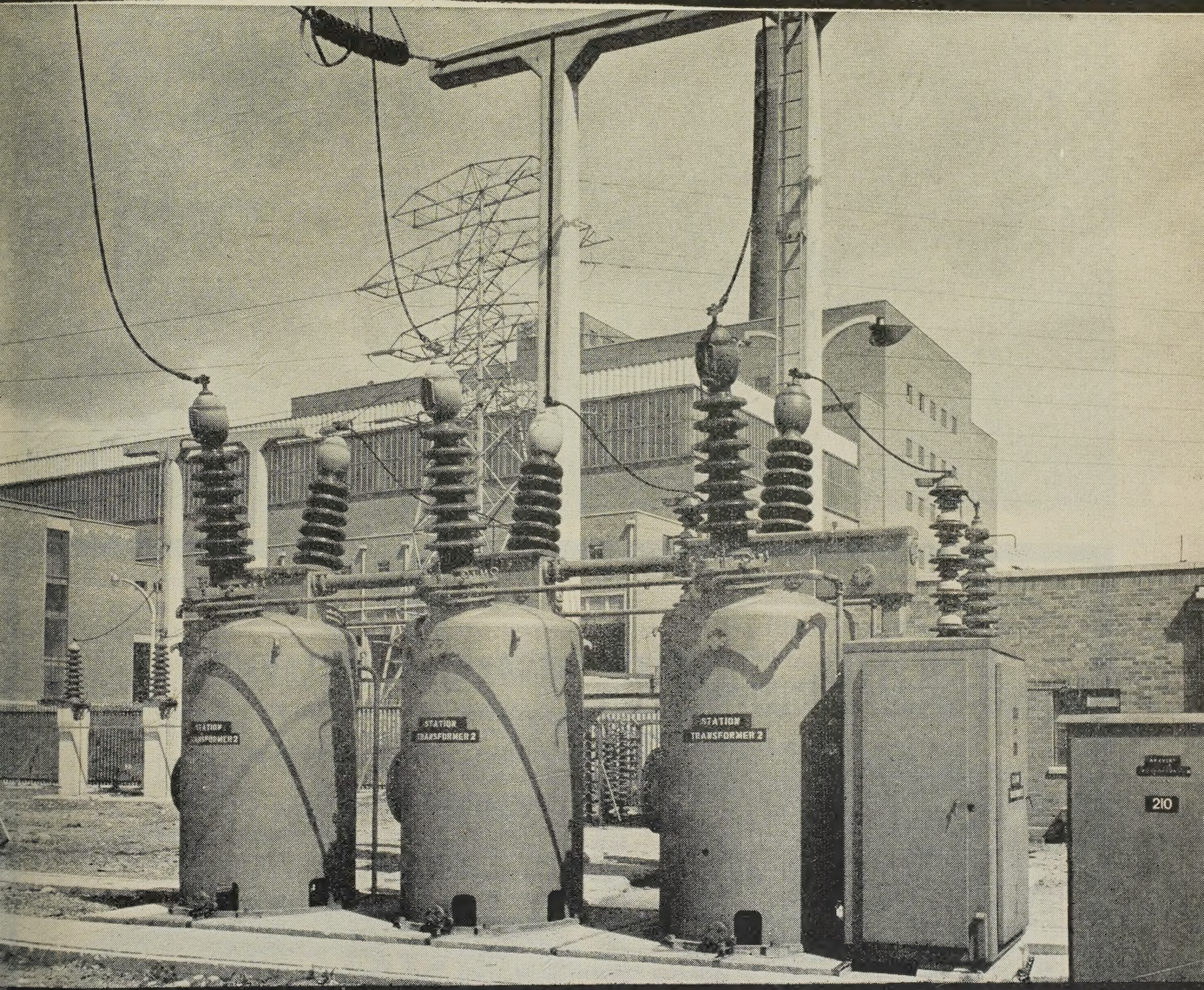

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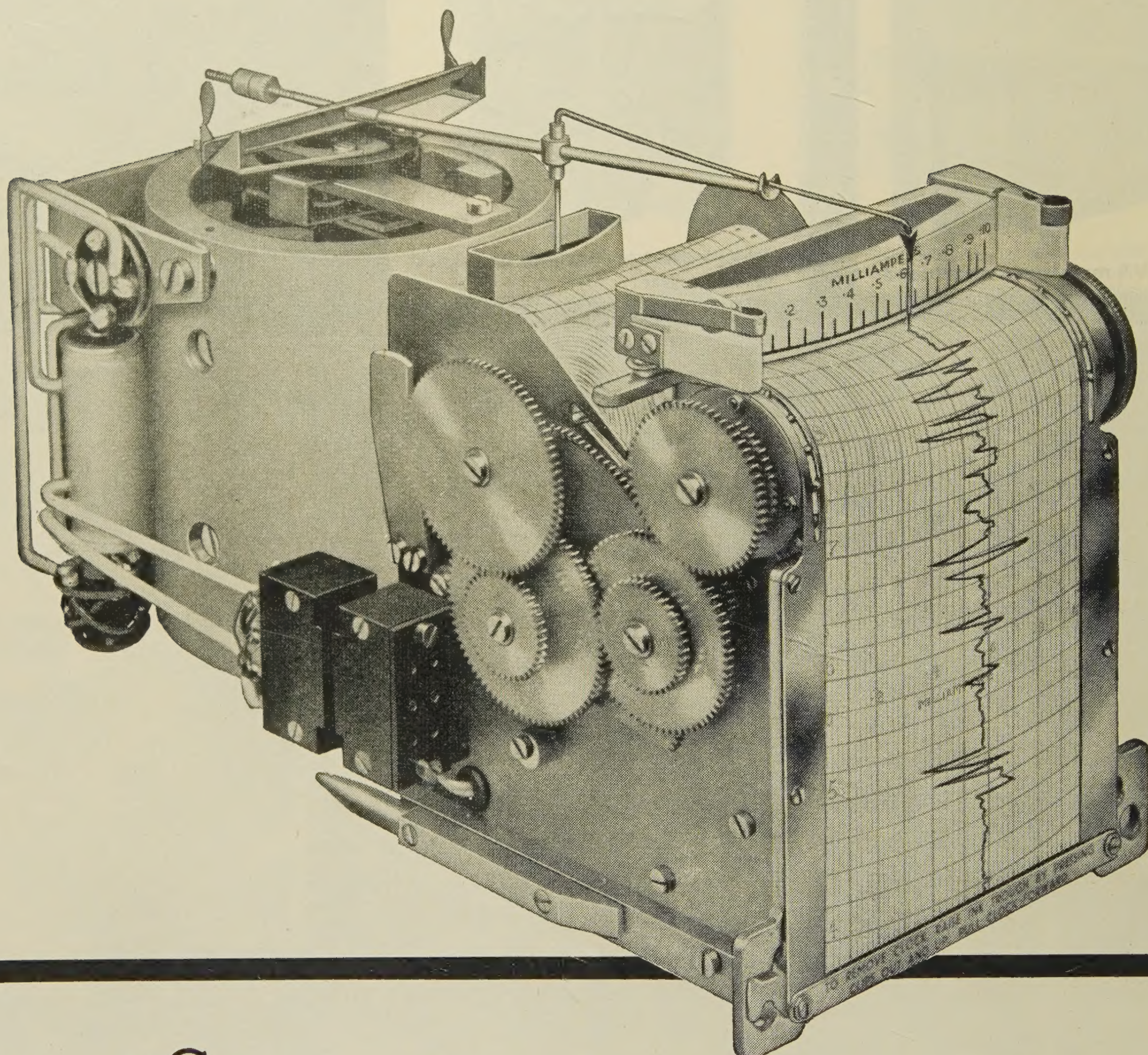

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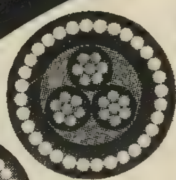
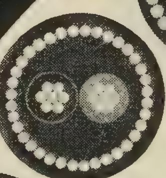

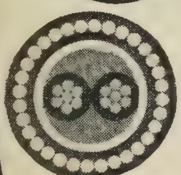

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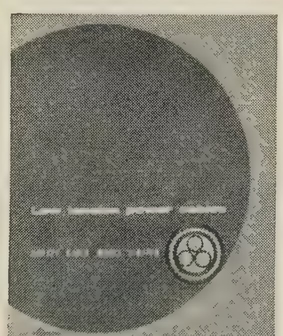

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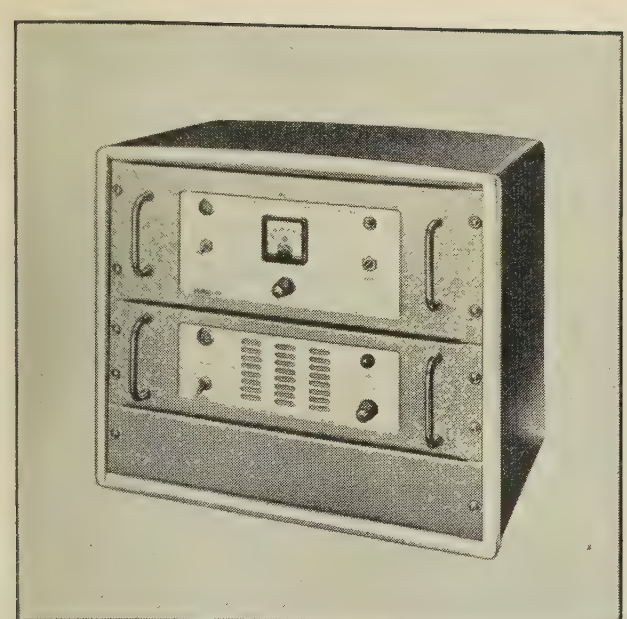

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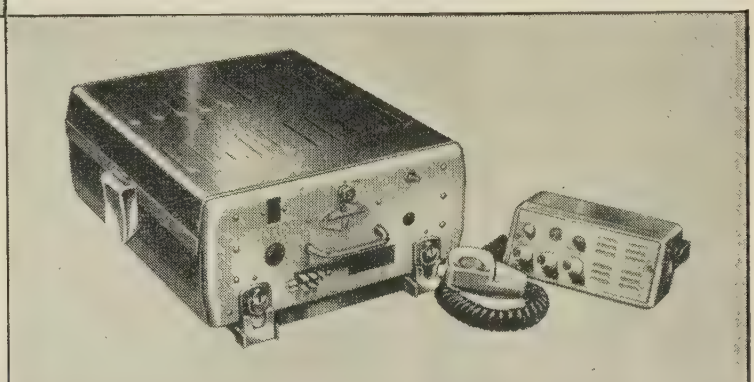

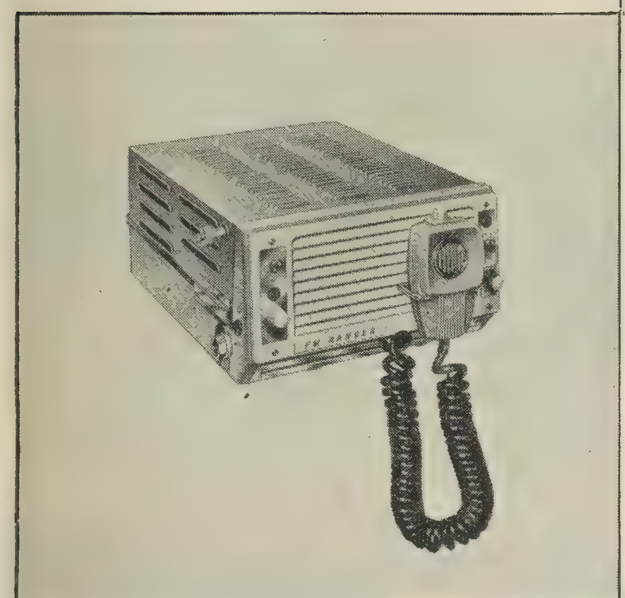

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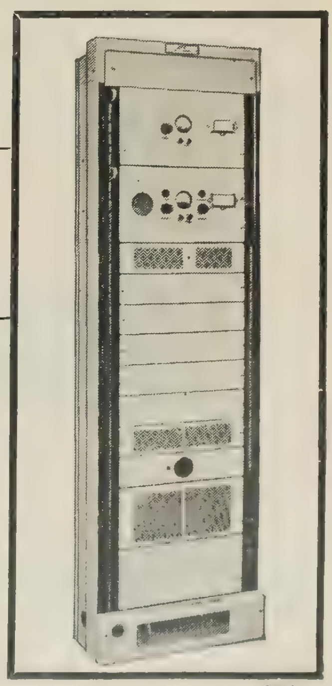

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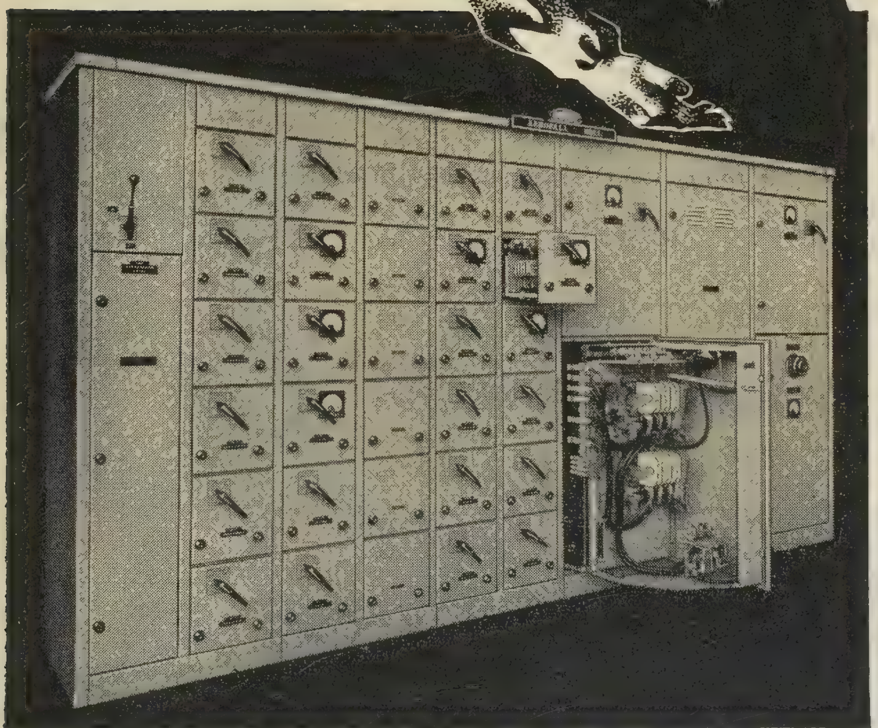

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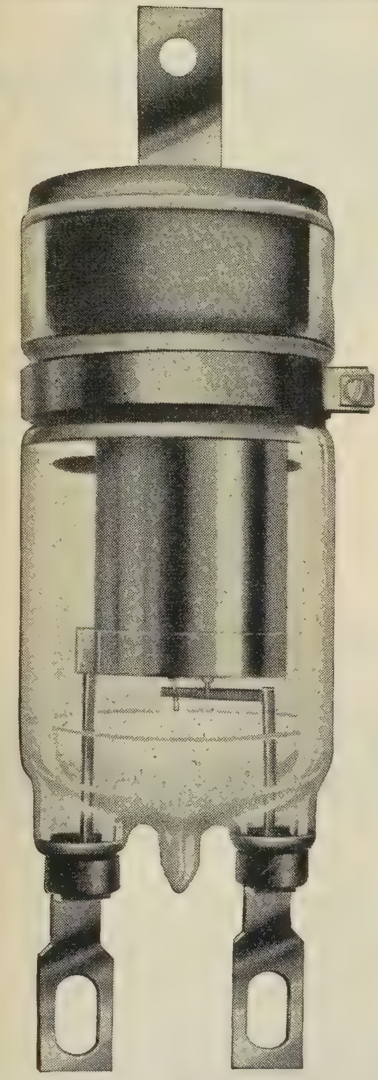

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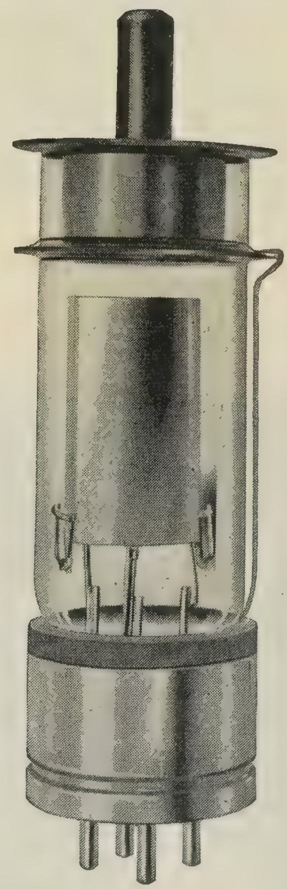

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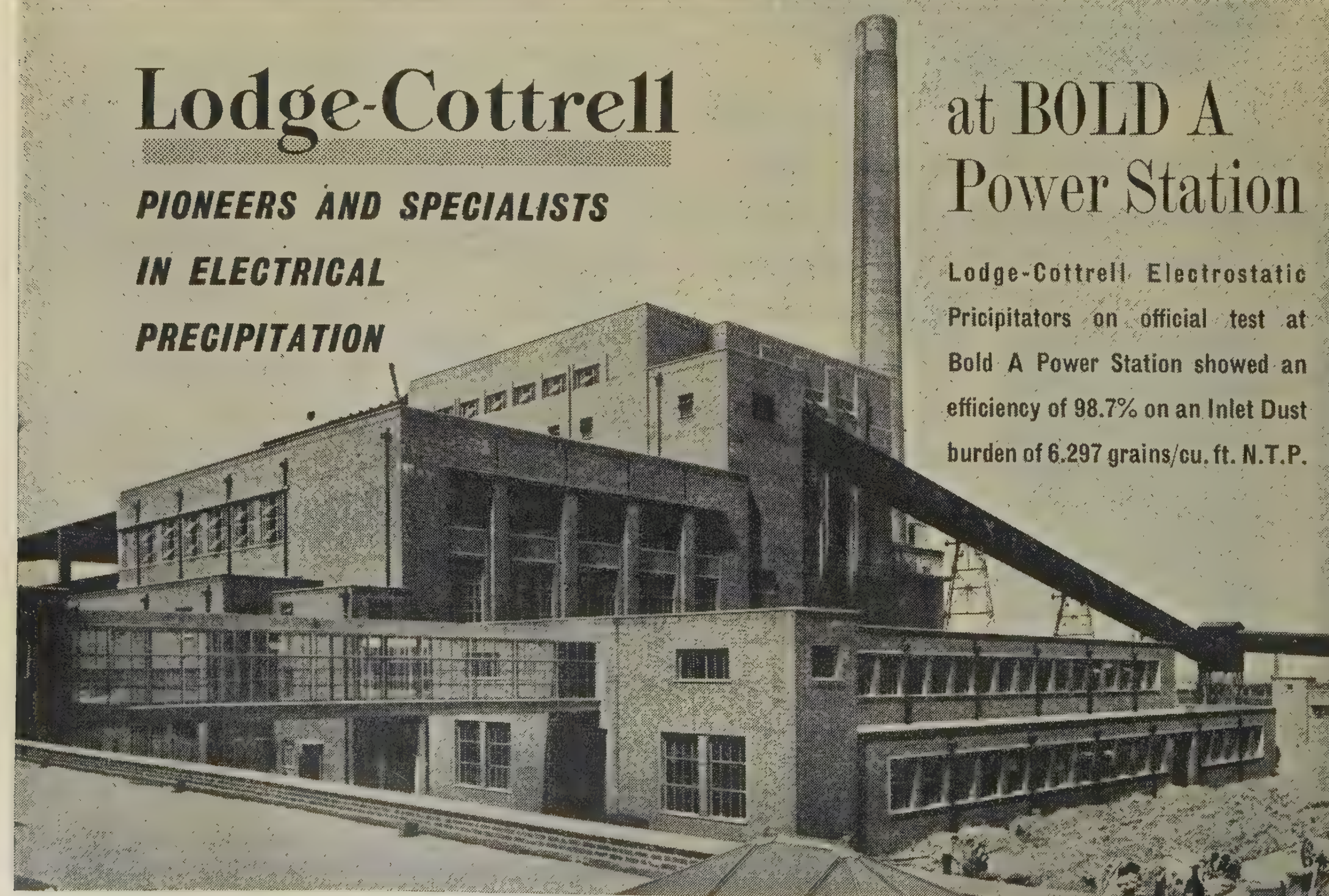

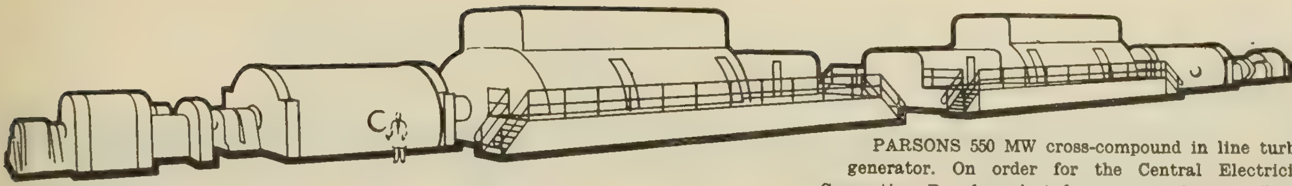

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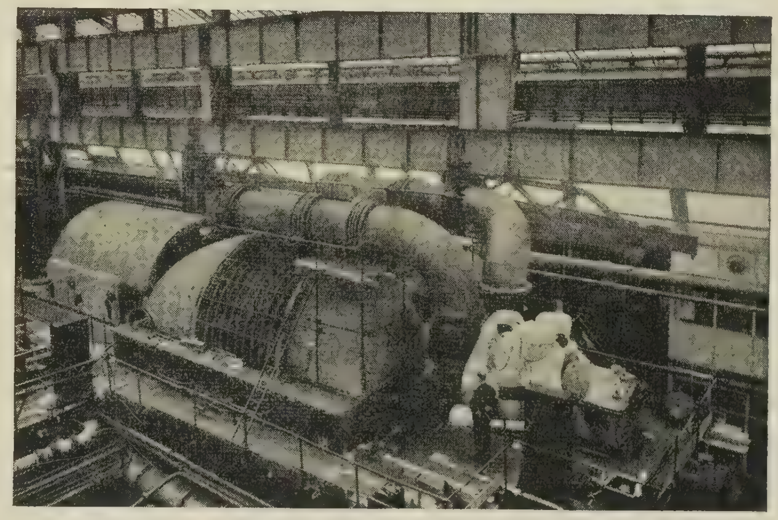

PARSONS 200 MW cross-compound turbo-generator (View of low pressure line only). Four of these machines are under construction for the Hydro Electric Power Commission of Ontario, Richard L. Hearn Generating Station. Steam conditions: 1,800 lb/ins² pressure, 1,000°F temperature, reheat to 1,000°F.

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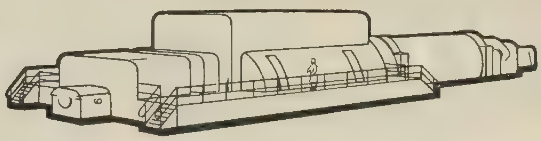

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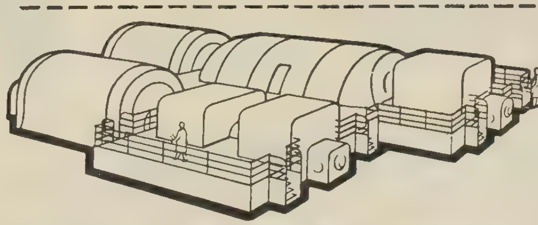

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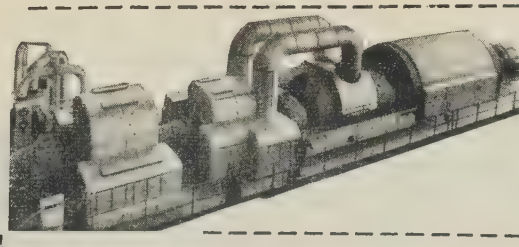

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The Institution of Electrical Engineers
Paper No. 2452 S
Dec. 1957

A METHOD OF ANALYSIS OF TRANSFORMER IMPULSE VOLTAGE DISTRIBUTION USING A DIGITAL COMPUTER

By BERYL M. DENT, M.Sc., E. R. HARTILL, B.Sc.(Eng.), Associate Member, and J. G. MILES, B.Sc.(Eng.), Associate Member.

(*The paper was first received 25th July, and in revised form 6th September,* 1957. *It was published in December,* 1957, *and was read before the* NORTH-WESTERN SUPPLY GROUP 25*th February, and a joint meeting of the* SUPPLY SECTION *and the* MEASUREMENT AND CONTROL SECTION 12*th March,* 1958.)

SUMMARY

With the increasing need for economical design of transformer insulation in large present-day power transformers, it is highly desirable to be able to predict at the design stage the distribution of impulse voltages throughout the windings. The paper presents a method of impulse voltage calculation using high-speed digital computer techniques which appears sufficiently accurate and flexible to provide a basis for a routine design procedure.

The derivation of the transformer equivalent circuit is discussed, together with the computer programme for the solution of the resulting differential equations. The advantages of the method are indicated, and the results are compared with other recent theoretical work and with direct tests on an experimental transformer.

The relative importance of the various winding parameters in the construction of the equivalent circuit is determined experimentally. Finally, possible extensions of the method are discussed and the possibility of complete automation of the procedure is indicated.

LIST OF SYMBOLS

C_{gk} = Total distributed capacitance to earth of winding section k.
$C_{G(k-1,\,k)}$ = Equivalent capacitance to earth between particular equivalent circuit divisions $(k-1)$ and k.
$C_{s(k-1,\,k)}$ = Total distributed series capacitance between particular sections $(k-1)$ and k.
C_{Sk} = Equivalent series capacitance for a particular equivalent-circuit division k.
$v(t)$ = Applied voltage wave.
i_k = Lower mesh current in division k.
i'_k = Upper mesh current in division k.
i_0 = Current through voltage source.
L_k = Self-inductance of equivalent-circuit division k.
M_{kq} = Mutual inductance between equivalent-circuit divisions k and q.
$p = \frac{d}{dt}$
P_{kq} = Matrix of inductances, defined in Section 12.1.
Q_{kq} = Matrix of capacitances, defined in Section 12.1.
$\phi_k = \int i_k dt$.
$\phi'_k = \int i'_k dt$.
$V_{k-1,k}$ = Voltage to earth at junction between divisions $(k-1)$ and k.
dV_k = Voltage difference across division k.
a, b, c, d, f, g = Constants defining the form of the applied voltage wave.

The convention of summation over a repeated suffix is adopted.

The authors are with the Metropolitan-Vickers Electrical Co. Ltd.

(1) INTRODUCTION

The distribution of impulse voltage in transformer windings has long been a factor of considerable significance in the design of high-voltage transformers. With the very large power transformers now being built, an accurate assessment of the voltage stresses likely to occur under surge conditions is essential in order that insulation dimensions may be kept to a minimum. The pioneer work of the Electrical Research Association[1] and others[2, 3] has led to a basic understanding of the phenomena involved, and work is now being directed towards a more precise analysis, particularly for the design of sectionalized windings.

The early work was based on standing-wave theory; for the sake of simplicity it assumed a unit-function applied voltage and transformer windings having uniformly distributed capacitance and inductance. Even with these assumptions the complete calculation was very laborious and unsuited to routine design work. Routine design was usually based[4, 5] on the initial (or capacitance) voltage distribution, augmented by recurrent-surge oscillograph records and impulse tests at high voltage.

More recently Rudenberg[6] and Norris[7] have given a good physical explanation of the phenomenon by the travelling-wave theory; but although the method of analysis proposed is fairly simple, it is admittedly approximate and takes no account of

the mutual inductance between winding sections or of the precise effect of different waveshapes, including chopped waves.

A recent paper by Lewis[8] considers the transformer winding as a ladder type of network having a finite number of uniform sections, and investigates the transient behaviour of such a network when subjected to a unit-function voltage surge. This leads to expressions for the voltage distribution which contain only a limited number of frequency components and which can readily be evaluated by numerical computation. In this method the mutual inductances between winding sections are not taken explicitly into account, although it is stated that their effect can be represented by the use of a modified value of self-inductance.

Experimental work by Abetti[9] in America indicates that results of sufficient accuracy for design purposes can be obtained using a scale-model transformer in conjunction with a recurrent-surge oscillograph and a capacitance network to simulate the series and earth capacitances of the winding. The method recognizes the practical difficulties which have always been present in this type of problem, namely the determination of the effective values of self- and mutual inductances, and the analysis for waveshapes other than unit function. From the design point of view, however, the method suffers the disadvantage that it requires the construction of a special model for each transformer, together with calculations of scaling factors and effective capacitance values. Realizing these difficulties, the equivalent circuit approach used by Lewis[8] has been modified by Waldvogel and Rouxel,[10] and McWhirter, Fahrnkopf and Steele,[11] who derive from it a set of circuit equations which are subsequently solved by some form of automatic computer. In both References 10 and 11, however, an analogue computer was used, with the result that limiting restrictions as regards size and symmetry of the equivalent circuit were imposed in the representation of the winding.

The work described in the present paper has been directed primarily towards the development of a method of calculation which would be suitable for use as a routine design procedure. The main requirement of such a method would be the ability to provide results of sufficient accuracy for engineering calculations in a reasonably short space of time, while remaining sufficiently flexible to permit of more detailed analysis where required.

The method uses an equivalent circuit of the same general form as that given by Lewis, but with certain significant differences. Any degree of non-uniformity can be present in the divisions of the equivalent circuit, and the effect of mutual inductances between divisions can be correctly taken into account. (It will be shown that this effect is different from that produced by a variation of the self-inductances.) The differential equations of the equivalent circuit are solved numerically by a high-speed digital computer, and the resultant voltage distribution is then printed out directly in tabular form. This is more convenient than the tedious photographic development and analysis in the experimental recurrent-surge-oscillograph technique. Any form of applied waveshape may be used, and the computer can also be used for the calculation of the winding constants and of the parameters of the equivalent circuit.

The present paper deals only with the development of the method and its application to an experimental transformer having a nearly uniform winding. A series of calculated solutions based on different assumptions in the representation of the winding are compared with each other and with experimental results obtained by means of a recurrent-surge oscillograph. By this means the relative significance of the various winding parameters on the transient voltage distribution is determined. Extension of the method to more complex transformers having substantially non-uniform windings will be described later, together with methods for obtaining more precise values of the winding constants.

(2) DEVELOPMENT OF EQUIVALENT CIRCUIT

(2.1) General

The condition of the normal impulse test is that a voltage impulse of known waveshape is applied between one end of one phase of a transformer winding and earth. The other end of the winding is usually at or near earth potential, while all the associated windings on the same phase are effectively earthed and fully or partially short-circuited.

If the earthing and short-circuiting of all windings except that under test were completely effective, the condition would be equivalent to the application of a surge voltage to an isolated winding; and in the development of the equivalent circuit which forms the basis of the present work such a condition has been assumed. Due to the practical limitations of providing effective earthing and short-circuiting of distributed windings, the voltage stresses obtained under actual impulse-test conditions are influenced to some extent by the presence of the other windings and particularly by the l.v. winding associated with the h.v. winding under test. It has been established, however, that the effect of the associated windings is to reduce the maximum inter-section voltages which are of primary concern to the design engineer, and thus the method to be described may be considered to give conservative design information for the h.v. inter-section voltages.

The equivalent circuit, whose development is described in the following Sections, thus represents the behaviour of a single distributed winding subject to an applied impulse voltage, which may be of any waveform capable of analytical expression. This circuit has been developed with the primary object of representing a sectionalized concentric winding in which each section can be regarded as having individual self-inductance, mutual inductances with all other sections, capacitance to earth, capacitance to adjacent sections and series self-capacitance between turns. With this type of winding, the application of any method of calculation which assumes a uniformly distributed winding is subject to error; and the representation of the winding by a ladder type of network appears to provide the greatest accuracy. The present equivalent circuit allows for the representation of all the winding parameters mentioned above, and can be applied without difficulty to non-uniform windings. In accordance with precedents established in previous work,[8] the effects of winding losses, time-variable inductances and inter-section capacitances other than those between adjacent sections are neglected, but the method is readily capable of extension to include these factors if they should be considered significant for a detailed analysis.

The size of the equivalent circuit is limited by the storage capacity of the computer used to solve the equations. It follows that in many cases the number of sections in the actual transformer winding will be greater than the number of divisions in the equivalent circuit. Therefore some divisions of the equivalent circuit may represent groups of winding sections while others represent only one winding section or part of a section. The manner in which the winding sections are grouped to form the equivalent-circuit divisions can be varied at the discretion of the transformer designer, so that significant portions of the winding (e.g. reinforced end-turns) can be examined in detail while less significant portions are grouped together.

(2.2) One Winding Section per Equivalent-Circuit Division

Fig. 1A is a schematic representation of a section-type winding showing the significant capacitances and inductances, the winding sections being numbered consecutively. It is assumed:

(a) That the total distributed capacitance of any winding section to earth, $C_{g(k)}$, can be represented by two lumped capacitances, each $\frac{1}{2}C_{g(k)}$, at either end of the section.

(b) That the total distributed capacitance between adjacent winding sections (k) and $(k+1)$, namely $C_{s(k,k+1)}$, can be represented by two lumped capacitances, each $\frac{1}{2}C_{s(k,k+1)}$, at either end of the sections.

The equivalent circuit derived from Fig. 1A is shown in Fig. 1B, where the equivalent-circuit divisions have been numbered to correspond with the winding sections. The parameters of the

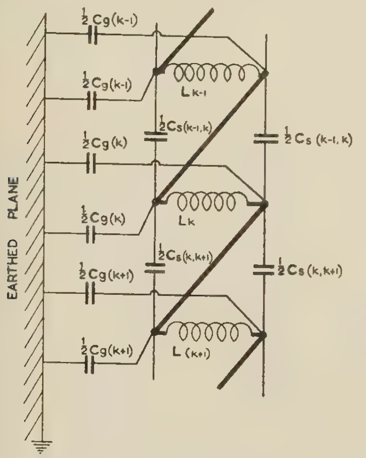

Fig. 1A.—Schematic representation of sectionalized winding.

Mutual inductances exist between all winding sections.

equivalent circuit are derived from those of the individual winding sections as follows:

$$C_{S(k)} = \tfrac{1}{2}[C_{s(k-1,k)} + C_{s(k,k+1)}] \quad . \quad . \quad . \quad (1)$$

$$C_{G(k-1,k)} = \tfrac{1}{2}[C_{g(k-1)} + C_{gk}] \quad . \quad . \quad . \quad . \quad (2)$$

$$C_{G(k,k+1)} = \tfrac{1}{2}[C_{gk} + C_{g(k+1)}] \quad . \quad . \quad . \quad . \quad (3)$$

(2.3) Grouping or Subdivision of Winding Sections to Form Equivalent-Circuit Divisions

Where the equivalent-circuit division represents several winding sections or a subdivision of a winding section (such as one or more individual turns), the parameters of the equivalent-circuit division will be derived in a manner similar to that shown above for one winding section per division, but the exact method of calculation will obviously vary for particular cases. In all cases, however, an equivalent circuit of the general form shown in Fig. 1B will finally be derived, in which an equivalent series capacitance will appear across the self-inductance of the division with part of the shunt capacitance to earth appearing at either end of the division. The values of the capacitance and self- and mutual inductances can either be calculated from first principles, perhaps using a digital computer, or obtained by means of an electrolytic tank.

(2.4) General Equivalent Circuit

Finally, a complete equivalent circuit for a section-type winding is shown in Fig. 1C. The winding is considered to be divided into n equivalent divisions, numbered consecutively from the end at which the voltage wave $v(t)$ is applied. Each equivalent division may represent any number of winding sections, and has an equivalent self-inductance L_k and equivalent mutual inductances M_{kq} ($q = 1$ to n, $q \neq k$) with other divisions, the latter values being reciprocal.

Each division has an equivalent series capacitance C_{Sk}, and between adjacent divisions are equivalent capacitances to earth $C_{(Gk-1,k)}$ . . . The equivalent capacitance to earth, $C_{G(0,1)}$, at the end of the winding at which the voltage $v(t)$ is applied, is equal to half the total capacitance to earth of the first equivalent-circuit division. The equivalent capacitance to earth at the earthed end of the winding is short-circuited by the earth connection.

Although this equivalent circuit is of the same general form as the ladder network described by Lewis,[8] there is now no restriction as to the uniformity of the various divisions; and in

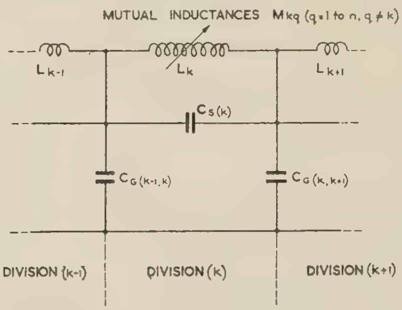

Fig. 1B.—Equivalent circuit for winding section, k, of Fig. 1A.

fact no additional difficulty is introduced in the calculation whatever the degree of non-uniformity. It should be noted, however, that the representation of the section-type winding by the equivalent circuit will be more exact if all the winding sections represented by any given equivalent division are nearly uniform. There can, however, be any degree of non-uniformity between successive divisions of the equivalent circuit without affecting the accuracy of the method.

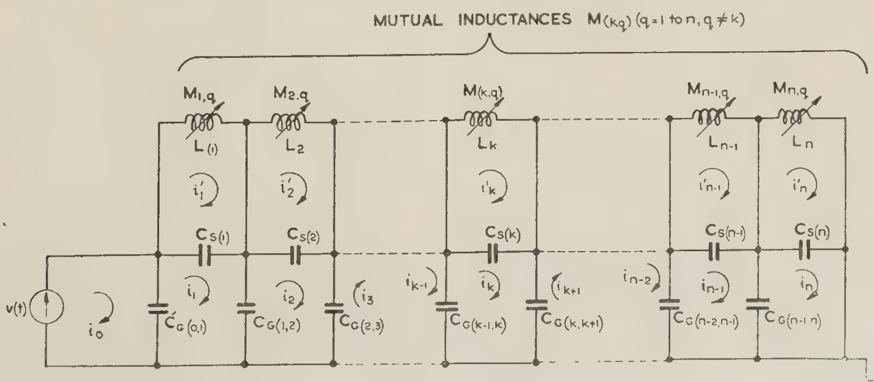

Fig. 1C.—General equivalent circuit for a transformer winding divided into n divisions.

It is probable that the winding sections near the line end will be of the greatest interest, since it is across these that the highest voltages arise. Moreover, the greatest degree of non-uniformity is to be expected in these sections. It follows that it may be advantageous for the equivalent-circuit divisions near the line end to represent individual winding sections (or even individual turns of a section), with a consequent greater number of sections per division at the earthed end of the winding.

The mutual inductances between divisions decrease rapidly as the distance between the divisions increases (see Appendix 12.3.3), and it may be possible to neglect many of the couplings between remote divisions with negligible effect on the solution. The generality of the method enables the validity of such simplifications to be readily established.

(3) GENERAL CIRCUIT EQUATIONS

The mathematical formulation of the equations is given in Appendix 12.1.

(3.1) Form of Applied Voltage

In general, the applied voltage can be of any waveform which is amenable to analytical expression. In the particular case of the unit-function wave a slight complication occurs in that the method of numerical integration used requires known initial conditions and therefore cannot deal directly with the discontinuity introduced at zero time. The required initial conditions are, however, obtained by a preliminary calculation of the initial voltage distribution, which is governed by the capacitances only. For this purpose the lower mesh equations only are solved, putting both the upper-mesh variables, ϕ_k', and the derivatives of the lower-mesh variables, $p\phi_k$, equal to zero.

The surge waveform, characteristic of those occurring during lightning phenomena and impulse testing, can be expressed generally as[14]

$$v(t) = a(\varepsilon^{-bt} - \varepsilon^{-ct}) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where a, b and c are constants which determine the shape of the wave.

The chopped waveform that is obtained by the flashover of protective equipment during a voltage surge can be regarded[14] as the superposition of two full waves, each of the general form given above. One of these component waves is positive and begins at zero time, while the other is negative and begins at the instant when chopping commences.

The surge waveform of most practical interest is the standard 1/50 wave used in impulse testing, both full and chopped. Analytical expressions for these waveshapes are given in Table 1,

Table 1

EXPRESSIONS FOR STANDARD IMPULSE WAVESHAPES

Waveshape	$v(t)$
1/50 (full)	$1{\cdot}0167(\varepsilon^{-0{\cdot}01423t} - \varepsilon^{-6{\cdot}0691t})$
1/50 (chopped) . .	$+1{\cdot}0167(\varepsilon^{-0{\cdot}01423t} - \varepsilon^{-6{\cdot}0691t})$ $-0{\cdot}9757[(\varepsilon^{-0{\cdot}0143(t-3)} - \varepsilon^{-86{\cdot}515(t-3)}]$

where time t is in microseconds and the maximum value of the wave is taken to be unity. In the case of the chopped waves, chopping is assumed to occur after 3 microsec with a time of chopping of 0·1 microsec.

The ability of the method to handle chopped waves is an important factor in its application as a routine design procedure, since the chopped-wave test gives rise to the most severe conditions and the resulting stresses are extremely difficult to calculate by other existing methods.

(4) SOLUTION BY ELECTRONIC DIGITAL COMPUTER

Eqns. (19) (Appendix 12.1) were solved on the Manchester University Electronic Computer Mark I.[12] This machine has an immediate-access store of 512 words of 20 binary digits each, and a magnetic-drum backing store with a capacity of 32768 words.

(4.1) Choice of Method

Originally, each second-order equation was replaced by two first-order equations

$$\left.\begin{aligned} p\phi_j &= \psi_j \\ p\psi_j &= F_{ji}\phi_i + (G_j p^2 + H_j)v(t) \end{aligned}\right\} \quad . \quad . \quad . \quad (5)$$

and the resulting sets of $2n$ simultaneous equations were integrated by the Runge–Kutta method. This method had two advantages, particularly for initial, exploratory work on a problem: no special method was necessary for starting the integration, and it was a simple matter to change the integration interval at any point in the range. Moreover, a library subroutine for this method was already available.

Subsequently, Prof. Hartree suggested an alternative method,[18] which takes advantage of the fact that the equations are linear second-order equations with the first derivative absent and with constant coefficients. This method is approximately three times as fast to run on the machine.

(4.2) Number of Divisions

The maximum number of equations which could be accommodated simultaneously in the high-speed store was 40. The number of divisions in the equivalent circuit was therefore chosen to be 20, giving 20 second-order or 40 first-order differential equations, represented by eqns. (5). The effect of changing the number of divisions has not yet been studied, but forms part of a schedule for future work.

(4.3) Step-Function Form of the Applied Voltage

$$v(t) = \begin{cases} 0 \text{ for } t < 0 \\ 1 \text{ for } t \geqslant 0 \end{cases}$$

In this case the equations were used in the form (5) with the initial values of ϕ determined by solving the n eqns. (15) [Appendix 12.1] with $\phi' = 0$ and $v(t) = 1$ (Section 3.1).

$$\left.\begin{aligned} &\text{i.e.} \quad Q_{jq}\phi_q = \delta_j \quad q, j = 1, 2 \ldots n \\ &\text{Also} \quad \psi_j = 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (6)$$

(4.4) Surge and Chopped Waveforms

$$v(t) = [a(\varepsilon^{-bt} - \varepsilon^{-ct}) - d(\varepsilon^{-f(t-t_1)} - \varepsilon^{-g(t-t_1)})]$$

It was found convenient to use the following transformation, which avoids the double differentiation of the input function $v(t)$:

$$\theta_j = \phi_j - G_j v(t)$$

Eqns. (5) then become

$$\left.\begin{aligned} p\theta_j &= \chi_j \\ p\chi_j &= F_{ji}\theta_i + (F_{ji}G_i + H_j)v(t) \end{aligned}\right\} \quad . \quad . \quad . \quad (7)$$

where the column matrix $(F_{ji}G_i + H_j)$ is independent of time and needs to be evaluated once only. The initial conditions,

$$\phi_j = \psi_j = 0$$

become

$$\left.\begin{aligned} \theta_j &= -G_j v(0) = 0 \\ \chi_j &= -G_i[pv(t)]_{t=0} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

(4.5) The Programme

The flow diagram for the programme is shown in Fig. 2.

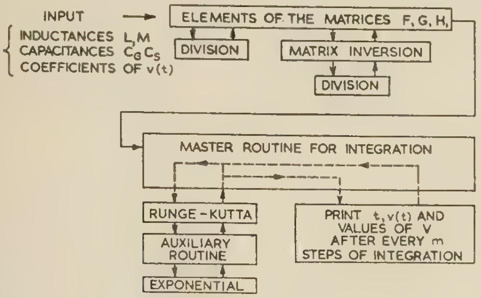

Fig. 2.—Flow diagram for computer programme.

The numerical data, which are fed into the computer immediately after the programme tape, consist of the self- and mutual inductances, L and M, the capacitances to earth between equivalent-circuit divisions, C_G, the corresponding series capacitances, C_S, and the coefficients of the applied waveform, $v(t)$. The programme first computes the elements of the matrix Q, followed by those of the matrices A and B. A is inverted and the matrices F, G and H are computed and stored. Each row of F is stored on a separate track on the drum, together with the corresponding elements of G and H. During the integration, the 40 values of the variables are kept in the fast store the whole time, and the rows of F read down in turn from the drum when required.

The master routine for integration sets the initial values of the variables [eqns. (6) or (8)], calls in the Runge–Kutta integration routine, and, after a specified number of steps, computes the values of V from eqn. (20) (Appendix 12.1) and prints t, $v(t)$ and the 19 values of V. The auxiliary routine computes the right-hand sides of eqns. (5) or (7), making use of a library sub-routine for the exponentials.

To facilitate a change of integration interval, the programme arranges for this quantity to be picked up from the hand switches.

The parameter which controls the number of integration steps before each printing is pre-set, but it can be altered quite easily, either by using the manual instruction switches or by reading into the machine a short piece of punched paper tape.

After each printing the values of the 40 variables are transferred from the fast store to the drum, so that if a machine failure affecting the fast store should occur, a restart could be made from the value of the time variable at the previous printing.

(5) VERIFICATION OF METHOD

As a first check the method was applied to obtain the surge voltage distribution in a 1000 kVA experimental transformer which was readily available, and on which voltage measurements with a recurrent-surge oscillograph could easily be made. Details of this transformer are given in Appendix 12.2. To ensure effective short-circuiting of the l.v. winding associated with the h.v. phase under test, a complete single-turn shield of copper foil was wrapped round it and was earthed.

Apart from a slight degree of reinforcement of insulation at the line end, the h.v. windings were substantially uniform and were treated as such, average values of the various parameters being calculated as described in Appendix 12.3. This enabled the results obtained to be compared, not only with direct measurements made by the recurrent-surge oscillograph, but also with calculations made by the method described by Lewis.[8] An estimate of the relative accuracies of the two methods of calculation could thereby be obtained.

For convenience in assessing the results the chief points of difference between the various methods are summarized below.

(*a*) *Applied wave.*—The applied wave used in the recurrent-surge oscillograph is essentially of the surge waveform described by eqn. (4), approximations to a step wave being produced by steepening the wavefront and lengthening the wavetail. Lewis's method assumes the application of a unit-function step wave.

(*b*) *Representation of winding parameters.*—Measurements made by the recurrent-surge oscillograph take into account all the capacitance, mutual-inductance and damping effects, and all the non-uniformities and non-linearities in the winding. The calculations made by Lewis's method are based on the assumption of a uniform winding, negligible inter-turn capacitance, inter-section capacitance negligible except between adjacent sections, and the effect of mutual-inductance linkages between sections ignored (except that these may be approximated to by using a modified value of self-inductance per section). In addition, the effects of resistance damping and time-variable inductances are ignored.

The present method ignores inter-section capacitance except between adjacent sections, resistance damping and saturation. It takes into account the effects of mutual inductance and of non-uniformity of winding. Inter-turn capacitance can be included as appropriate.

Although in principle the number of equations of the general form shown in eqn. (19) which can be solved by a digital computer (using a series of sub-routines to complement the storage facilities of the computer itself) is unlimited, it was decided, for the first application of the method, to limit the equations to a number which could be solved by the use of existing programmes. This meant a practical limit of 20 equations, and consequently the equivalent circuit was restricted to the same number of divisions. It was also decided to group the transformer winding sections uniformly into the equivalent-circuit divisions, and since the experimental transformer has 58 sections, each equivalent division represents 3 winding sections except the division adjacent to the neutral point, which represents 1 winding section.

(6) RESULTS

In order to assess the relative significance of the various factors involved in the representation of the winding by the equivalent circuit (Appendix 12.3), a series of calculations was carried out, each based on a different representation of the winding parameters, the generality of the method lending itself well to such comparative evaluation. The various factors considered were:

(*a*) Effect of mutual inductances between sections.
(*b*) Effect of inter-turn capacitance.
(*c*) Electrostatic fringing effects near the yoke.

(6.1) Effect of Mutual Inductances between Sections

Figs. 3 and 4 show for comparative purposes the distribution of surge voltage to earth throughout the winding at various times following the application of a unit-function wave, with and

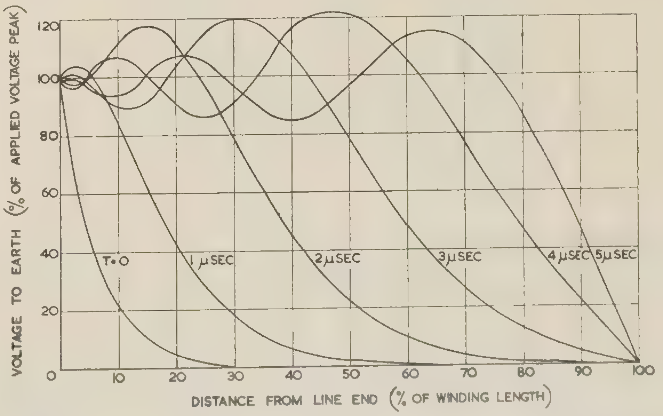

Fig. 3.—Calculated distribution of voltage to earth throughout winding (mutual inductances neglected).

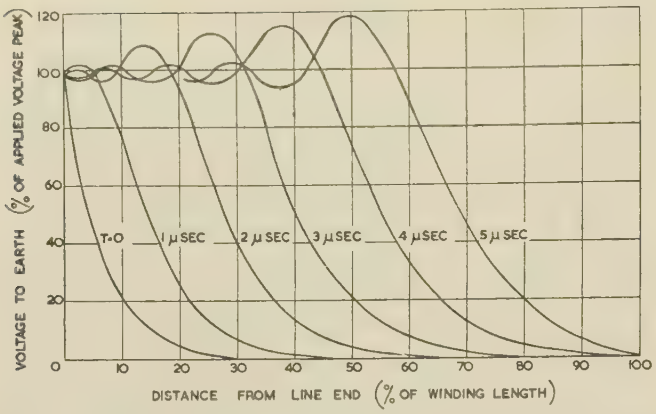

Fig. 4.—Calculated distribution of voltage to earth throughout winding (mutual inductances included).

without mutual coupling, and indicate the progress of the travelling wavefront along the winding.

Fig. 3 was obtained by the method described in the present paper, using calculated average values of the winding parameters (see Appendix 12.3) and ignoring all mutual inductances and inter-turn capacitance. These curves are identical with those obtained from formulae given by Lewis[8] for corresponding time intervals.

Fig. 4 shows the corresponding curves obtained when estimated values for mutual inductances (see Appendix 12.3.3) are included in the calculation. It will be seen that the effect is to change both the velocity of the travelling wave and also the slope of the wavefront. Examination of Lewis's formula for the standing-wave solution shows that modification of the self-inductance will vary the time scale only and is therefore not an adequate means of representing mutual coupling.

The effect of mutual inductance on the inter-section voltage is illustrated in Figs. 5A, 5B and 5C, which show the voltage

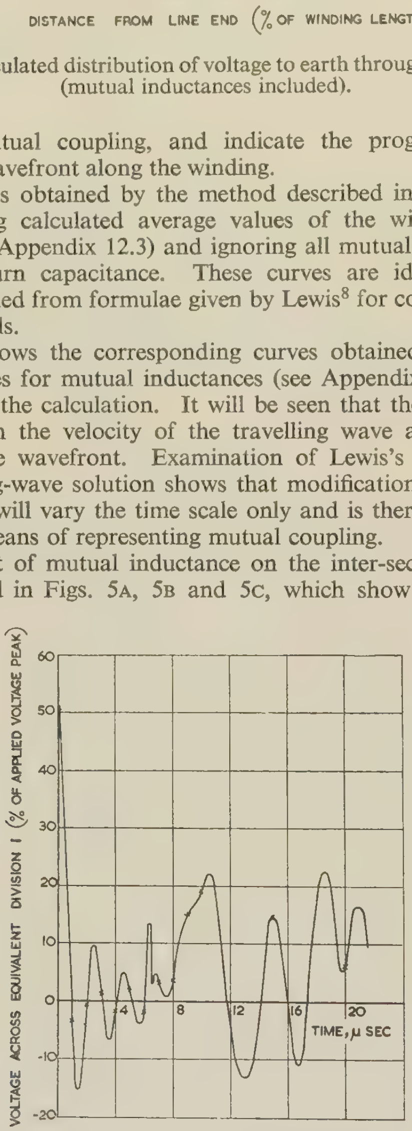

Fig. 5A.—Calculated voltage across first three winding sections (mutual inductances neglected).

× Results obtained by Lewis's method.

appearing across the first three sections of the transformer winding (i.e. the first equivalent division of the equivalent circuit) as a function of time. Fig. 5A is obtained without mutual inductances, and the superimposed points are those found from Lewis's formula. It is seen that while exact agreement

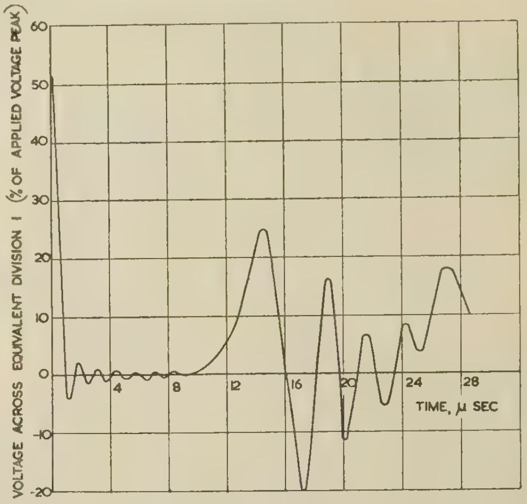

Fig. 5B.—Calculated voltage across first three winding sections (mutua inductances included).

Fig. 5C.—Measured voltage across first three winding sections.

between the isolated points and the curve is obtained, the tim intervals between the former (which were calculated by a des computer) are so large that many of the significant oscillation are missed. This indicates that, even in the application of th formulae given by Lewis, the use of an automatic compute would be essential to obtain results of sufficient accuracy.

Fig. 5B shows the corresponding curve when the estimate mutual inductances are included, and this agrees well wit Fig. 5C, which is the record obtained from the recurrent-surg oscillograph.

Comparison of Figs. 5A and 5B shows clearly that the inclusio of mutual inductances has a significant effect on the form of th travelling wave as well as its velocity.

In comparing Figs. 5A and 5B with Fig. 5C, it should be note that, whereas the calculated results assume a unit-functio applied wave, the nearest approximation to this which could b obtained on the recurrent-surge oscillograph was a 0·1/15 wave.

(6.2) Representation of Winding Capacitance

The most severe inter-section voltage stresses are those whic occur across the winding sections adjacent to the line end imme diately subsequent to the application of the impulse voltag and which are associated with the initial voltage distributio along the winding.[5] For uniform windings the latter is normall expressed in terms of the parameter

$$\alpha = \sqrt{(C_G/C_S)}$$

The instantaneous voltage developed across the first few turr of a winding, however, is determined by an effective value of for these turns which differs from the value normally obtaine by assuming a uniform winding. This is apparent from Figs. and 7—Fig. 6 showing the initial voltage distribution, and Fig. the maximum inter-section voltages occurring throughout th winding. In each Figure, curve (*a*) shows the results obtaine

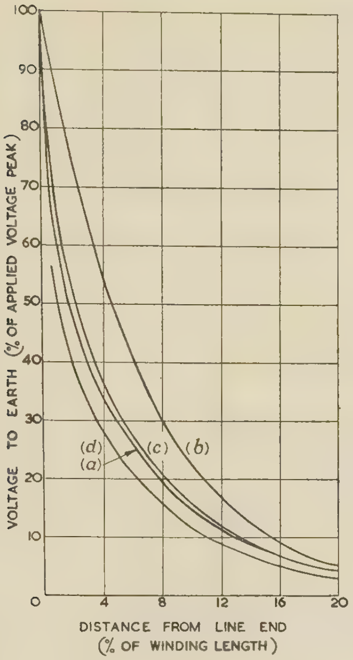

Fig. 6.—Initial voltage distribution throughout winding.

(*a*) Measured result.
(*b*) Calculated result neglecting inter-turn capacitance.
(*c*) Calculated result including inter-turn capacitance.
(*d*) As (*c*) but with C_{G1-2} = twice calculated value.

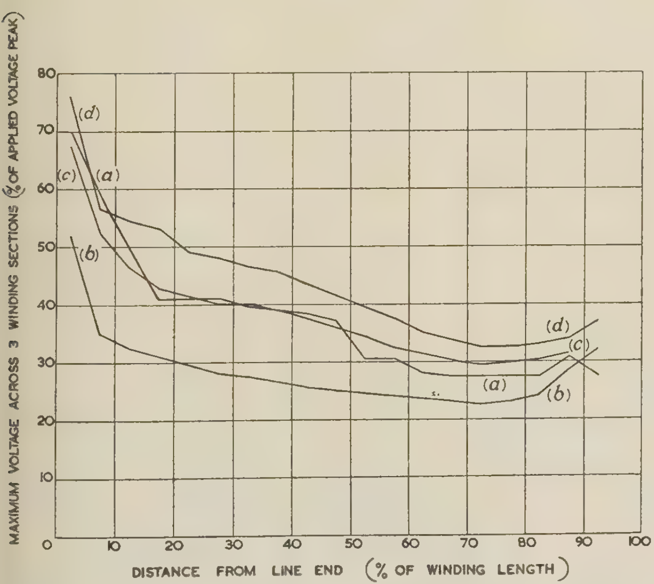

Fig. 7.—Maximum inter-section voltages throughout winding.

(*a*) Measured result.
(*b*) Calculated result neglecting inter-turn capacitance.
(*c*) Calculated result including inter-turn capacitance.
(*d*) As (*c*), but with C_{G1-2} = twice calculated value.

from the recurrent-surge oscillograph and curve (*b*) the calculated result based on the same assumptions as in Fig. 5B.

The effective value of α for the turns near the line end is determined by two factors:

(*a*) The presence of inter-turn capacitance, which modifies the effective series capacitance for this part of the winding.

(*b*) The increase in effective capacitance to earth due to possible fringing effects in the electric flux distribution in the neighbourhood of the yoke.

To investigate the relative effects of these factors, successive calculations were made with modified values of the winding capacitances. These modifications were introduced in two stages.

First, the various capacitances were recalculated to include inter-turn capacitance. The grouping of the equivalent circuit is still uniform in that each equivalent division (with the exception of the last) represents three winding sections as before, but because of the inclusion of inter-turn capacitance the series capacitances, C_S, in the various equivalent-circuit divisions now become unequal. Curves (*c*) in Figs. 6 and 7 show respectively the initial voltage distribution and the maximum inter-section voltages for this case.

Secondly, the effective increase in the shunt capacitance to earth at the line end of the winding was allowed for by increasing $C_{G(1,2)}$ (see Fig. 1c) by a factor of 2. The resulting curves are shown as curves (*d*) of Figs. 6 and 7.

It is apparent from Figs. 6 and 7 that the inclusion of inter-turn capacitance in the calculation gives results which are in good agreement with the measured values, although the calculated inter-section voltages across the sections near the line end are rather too low [Fig. 7, curve (*c*)]. Doubling the line-end capacitance to earth, $C_{G(1,2)}$, gives voltage stresses greater than the measured values [Fig. 7, curve (*d*)]. It may be concluded that, while the inter-turn capacitances are of considerable significance in determining the inter-section voltage stresses, the effect of flux fringing is slight.

(6.3) Effect of Waveshape

All the computational work described hitherto has utilized a unit-function applied voltage, since this forms the basis of most other published methods of calculation.[6, 7, 8] As has been pointed out, however (Section 6.1), surge voltages of this form were not obtainable in practice, the nearest approximation which was available on the recurrent-surge oscillograph being a 0·1/150 wave, in which the departure from the infinite wavetail of the unit function was clearly apparent. It has been shown in previous work[7] that the principal effect of a finite wavetail is to reduce the voltages to earth developed in the body of the winding. This effect is indicated in Figs. 8A and 8B, which show the calculated voltages to earth at points 10% and 40% down the winding respectively; and Fig. 9, which shows the distribution of maximum voltage to earth throughout the winding. Figs. 8A and 8B

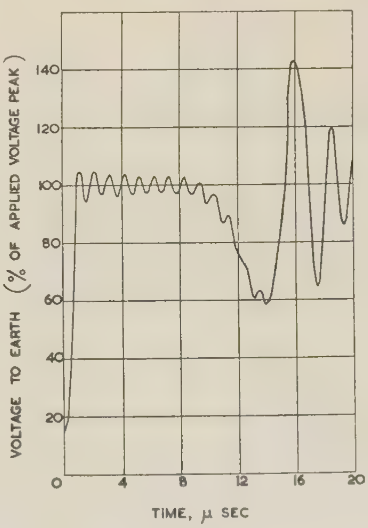

Fig. 8A.—Calculated voltage to earth at 10% of winding from line end (unit-function applied wave).

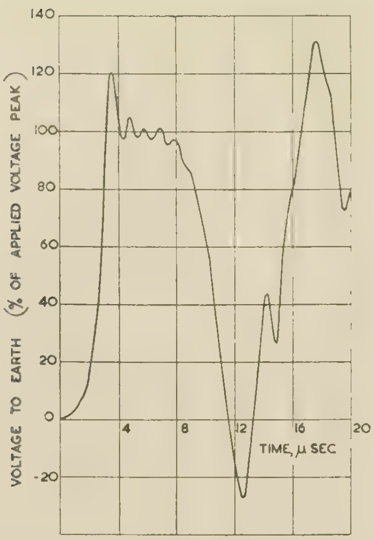

Fig. 8B.—Calculated voltage to earth at 40% of winding from line end (unit-function applied wave).

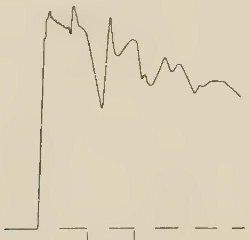

Fig. 8C.—Measured voltage to earth at 10% of winding from line end (0·1/150 wave applied by recurrent-surge oscillograph).

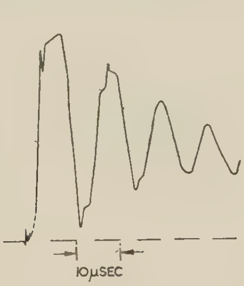

Fig. 8D.—Measured voltage to earth at 40% of winding from line end (0·1/150 wave applied by recurrent-surge oscillograph).

and curve (*a*) of Fig. 9 were calculated using a unit-function applied wave and including the effect of mutual inductance and inter-turn capacitance. The corresponding experimental curves, Figs. 8C and 8D and curve (*b*) of Fig. 9, were obtained by the recurrent-surge oscillograph using a 0·1/150 applied wave.

(6.4) Attenuation

The attenuation observed in the measured results is due partly to winding resistance and partly to eddy-current loss. If desired, these factors may be included in the calculation by a modification of the circuit equations; but since they affect principally the voltages to earth, which are not of critical significance in design, and since the method in its present form gives conservative results for these voltages, this modification may in most cases be considered unnecessary.

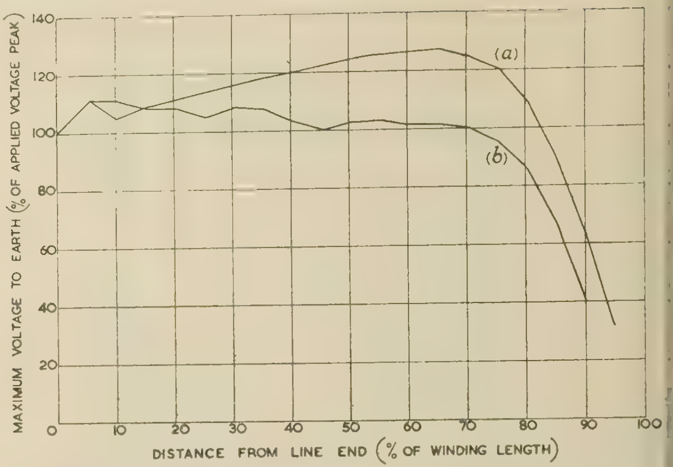

Fig. 9.—Maximum voltages to earth throughout the winding.

(*a*) Calculated result with unit-function applied wave.
(*b*) Measured result with 0·1/150 applied wave.

(6.5) Effect of L.V. Shield

Fig. 10 shows the measured maximum inter-section voltages with and without shielding of the l.v. winding associated with the h.v. winding under test. It is apparent that the important

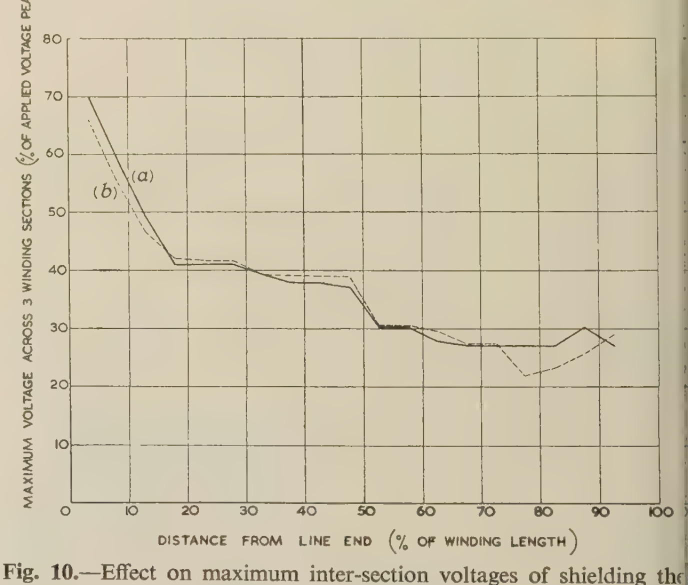

Fig. 10.—Effect on maximum inter-section voltages of shielding the winding of the phase under test.

(*a*) Measured result with l.v. shield.
(*b*) Measured result without l.v. shield.

inter-section voltages near the line end are increased by the presence of the shield, and it follows that the method of calculation described will give results for these voltages which are slightly pessimistic as compared with those obtained under practical impulse conditions. If more exact results are required in a particular case they may be obtained by appropriate modification of the equivalent circuit.

(7) COMPUTING TIMES

By inspection of Figs. 3, 5A and 8 and similar records, it is readily established that, when considering waveforms of practical interest, the maximum values of voltage to earth and inter-section voltages throughout the winding are associated with the first passage of the travelling wavefront down the winding

hese voltage maxima are of primary interest to the design ngineer. In the later stages of the transient, various secondary actors become significant, e.g. flux penetration, winding losses, tc. These factors are not included in the equivalent circuit as resented here, since it is considered sufficient to continue the omputation in any particular case only to a point corresponding o the time required for the wave to travel once down the winding. 'or the transformer under consideration this time was approxi- nately 9 microsec.

The time taken for any given computation depends on two actors:

(*a*) The integration intervals necessary to obtain the necessary accuracy in the numerical integration process employed.

(*b*) The printing intervals necessary to afford accurate observation of the rapid voltage oscillations, particularly across the winding sections near the line end.

In the calculations described in the paper each step of inte- ration took 24 sec, and each complete printing operation 32 sec. 'he maximum permissible time intervals (referred to problem ime in microseconds) were found to be:

Integration ..	.. 0 (0·025) 5·0 (0·05) 10·0
Printing ..	.. 0 (0·05) 1·5 (0·1) 5·0 (0·25) 10·0

On this basis the time taken for one complete calculation is h 13 min, which at a representative charge for computer time f £40 per hour corresponds to a cost of £89.

(8) FUTURE EXTENSIONS OF METHOD

The scope and flexibility of modern electronic digital com- uters make possible many modifications and improvements to he method of calculation described in the paper. In particular, will be possible to assess accurately the effect of various econdary factors such as winding resistance and non-linear or me-variable inductances. These factors have not been included n the equivalent circuit which forms the basis of the present nethod, since it has previously been generally accepted that their ffect on the early progress of the transient is negligible. More- ver, the calculation of these quantities is far from exact. How- ver, by a suitable modification of the circuit equations, assumed r calculated values of these factors can readily be introduced nd their effects on the solution assessed.

The calculation of the various circuit parameters can be arried out by means of computer sub-routines, the relevant ormulae being derived partly from theoretical considerations nd partly by experimental investigations with an electrolytic ank.[13] The calculation of the impulse voltage distribution an then be reduced to a routine process, the only information equired being a sheet giving the dimensions of core and windings f one phase of the transformer, and the waveform of the pplied voltage.

The current flowing in the neutral under impulse test conditions frequently of interest as giving an indication of any insulation ilure occurring during the test. By the present method of alculation it is possible to compute the value of this current nd to examine the effects of faults at various positions along e winding for a proposed new design.

A further simple application of the new method would be the alculation of transformer reactances and forces from the same t of design dimensions (copper to copper and copper to core, c.), as were used for the voltage distribution calculation.

(9) CONCLUSIONS

A method of calculation of impulse voltage distribution in ansformer windings using a general-purpose digital computer as been developed which is suitable for use as a routine design edure.

The method is readily applicable to non-uniform windings and to any form of applied voltage wave including chopped waves. The results are obtained conveniently in tabular form. The method may be readily extended to include such secondary effects as winding resistance and variable inductances. It can also be used for the calculation of neutral current, including the effect of faults at different positions of the winding, and of various chopping times of the rod gap.

Application of the method to a substantially uniform winding has shown that, in order to obtain correct values of the important inter-section voltages near the line end of the winding, it is necessary to include the effect of inter-turn capacitance, which requires the representation of the uniform winding by a non-uniform equivalent circuit. It has also been established that specific representation of the mutual inductances between the various winding sections is essential.

In view of the inherent flexibility of the method, it is considered that the present work provides a suitable basis for the more detailed analysis of surge voltage distribution under the complex conditions encountered in practice.

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(12) APPENDICES

(12.1) Formulation of Equations

Mesh currents i_o, i_k, i'_k, are defined as shown in Fig. 1c, where i_o is the current through the voltage source, i_k is the current in the lower mesh of division k and i'_k the current in the upper mesh of division k. A simplification in the form of the equations is achieved by replacing the current variables i by functions ϕ_k, ϕ'_k, where

$$\phi_k = \int i_k dt$$
$$\phi'_k = \int i'_k dt$$

A mesh analysis of the general equivalent circuit of Fig. 1c then yields the following groups of equations (where $p = d/dt$):

Group 1 (*upper meshes*).

$$0 = \left(L_k p^2 + \frac{1}{C_{Sk}}\right)\phi'_k - \frac{1}{C_{Sk}}\phi_k + \sum_{\substack{q=1\\q\neq k}}^{q=n} M_{kq}p^2\phi'_q;\ (k = 1, 2 \ldots n) \quad . \quad . \quad . \quad . \quad (9)$$

These equations may be written in matrix form as follows:

$$P_{kq}p^2\phi'_q = \frac{1}{C_{Sk}}(\phi_k - \phi'_k) \quad . \quad . \quad . \quad . \quad (10)$$

where P_{kq} is the $(n \times n)$ symmetric matrix

$$\begin{vmatrix} L_1 & M_{12} & M_{13} \ldots M_{1n} \\ M_{21} & L_2 & M_{23} \ldots \\ M_{31} & M_{32} & L_3 \quad \ldots \\ \cdots & \cdots & \cdots \\ M_{n1} & \cdots & \cdots L_n \end{vmatrix}$$

Group 2 (*lower meshes*).

For $k = 0$,

$$v(t) = \frac{1}{C_{G(0,1)}}\phi_0 - \frac{1}{C_{G(0,1)}}\phi_1 \quad . \quad . \quad . \quad (11)$$

For $k = 1$ to $k = (n-1)$,

$$0 = -\frac{1}{C_{G(k-1,k)}}\phi_{k-1} - \frac{1}{C_{Sk}}\phi'_k + \left[\frac{1}{C_{G(k-1,k)}} + \frac{1}{C_{Sk}} + \frac{1}{C_{G(k,k+1)}}\right]\phi_k - \frac{1}{C_{G(k,k+1)}}\phi_{k+1} \quad . \quad (12)$$

For $k = n$,

$$0 = -\frac{1}{C_{G(n-1,n)}}\phi_{n-1} - \frac{1}{C_{Sn}}\phi'_n + \left[\frac{1}{C_{G(n-1,n)}} + \frac{1}{C_{Sn}}\right]\phi_n \quad . \quad (13)$$

The quantities of primary interest are the voltages appearing between the various sections and earth, and the voltages between sections. These can be derived from a knowledge of the lower mesh currents only. The upper mesh currents are not required and it will be advantageous to eliminate them from the calculation.

Adding the equation for $k = 0$ to that for $k = 1$,

$$v(t) = -\frac{1}{C_{S1}}\phi'_1 + \left[\frac{1}{C_{S1}} + \frac{1}{C_{G(1,2)}}\right]\phi_1 - \frac{1}{C_{G(1,2)}}\phi_2 \quad . \quad (14)$$

so that the set of n equations may be written in the form

$$Q_{kq}\phi_q - \frac{1}{C_{Sk}}\phi'_k = \delta_k v(t) \quad . \quad . \quad . \quad . \quad (15)$$

where $\delta_k = 1$ for $k = 1$
$= 0$ for $k \neq 1$

and Q_{kq} is the following $(n \times n)$ symmetric matrix, each row of which contains 3 non-zero elements which lie on and adjacent to the main diagonal:

$$\begin{vmatrix} \left[\frac{1}{C_{S1}} + \frac{1}{C_{G(1,2)}}\right] & -\frac{1}{C_{G(1,2)}} & 0 & 0 & 0 \\ -\frac{1}{C_{G(1,2)}} & \left[\frac{1}{C_{G(1,2)}} + \frac{1}{C_{S2}} + \frac{1}{C_{G(2,3)}}\right] & -\frac{1}{C_{G(2,3)}} & 0 & 0 \\ 0 & -\frac{1}{C_{G(2,3)}} & \left[\frac{1}{C_{G(2,3)}} + \frac{1}{C_{S3}} + \frac{1}{C_{G(3,4)}}\right] & -\frac{1}{C_{G(3,4)}} & -\frac{1}{C_{G(n-1,n)}} \\ 0 & 0 & 0 & 0 & -\frac{1}{C_{G(n-1,n)}}\left[\frac{1}{C_{G(n-1,n)}} + \frac{1}{C_{Sn}}\right] \end{vmatrix}$$

A set of n simultaneous differential equations of the second order for the ϕ variables may be deduced by the following matrix manipulations:

From (15),

$$\left.\begin{aligned} \frac{1}{C_{Sk}}\phi'_k &= Q_{kq}\phi_q - \delta_k v(t) \\ \phi'_q &= C_{Sq}Q_{qj}\phi_j - C_{Sq}\delta_q v(t) \end{aligned}\right\} \quad . \quad . \quad . \quad (16)$$

Substituting in (10),

$$P_{kq}C_{Sq}Q_{qj}p^2\phi_j - P_{kq}C_{Sq}\delta_q p^2 v(t) = \frac{1}{C_{Sk}}\phi_k - Q_{kq}\phi_q + \delta_k v(t) \quad . \quad . \quad . \quad . \quad (17)$$

or:

$$P_{kq}C_{Sq}Q_{qj}p^2\phi_j = \left(\frac{1}{C_{Sk}}\phi_k - Q_{kq}\phi_q\right) + (P_{k1}C_{S1}p^2 + \delta_k)v(t) \quad . \quad . \quad . \quad . \quad (18)$$

or:

$$A_{kj}p^2\phi_j = -B_{kj}\phi_j + (C_kp^2 + D_k)v(t) \quad . \quad . \quad (18)$$

where

$$A_{kj} = P_{kq}C_{Sq}Q_{qj}$$

$$B_{kj}\phi = Q_{kj}\phi_j - \frac{1}{C_{Sk}}\phi_k$$

$$C_k = C_{S1}P_{k1}$$

$$D_k = \delta_k$$

A and B are square matrices of rank n.
C and D are column matrices with n elements.
B is symmetrical, but in general A is unsymmetrical.

Multiplying eqn. (18) by A_{jk}^{-1},

$$p^2\phi_j = F_{ii}\phi_i + (G_jp^2 + H)v(t) \quad . \quad . \quad . \quad (19)$$

where

$$F_{ji} = -A_{jk}^{-1}B_{ki}$$
$$G_j = A_{jk}^{-1}C_k$$
$$H_j = A_{jk}^{-1}D_k$$

The initial conditions are $\phi_j = p\phi_j = 0$ $(j = 1, 2 \ldots n)$ except when the applied voltage is a step function. This case is dealt with in Section 3.1.

The voltages to earth at the junction points between the equivalent circuit divisions are given by the following equation:

$$V_{k-1,k} = \frac{1}{C_{G(k-1,k)}}(\phi_{k-1} - \phi_k) \quad . \quad . \quad . \quad (20)$$

$V_{0,1}$ is equal to the applied voltage $v(t)$.

The voltage differences, dV, across the divisions are given by the first differences of the nodal voltages:

$$dV_k = V_{k-1,k} - V_{k,k+1} \quad . \quad . \quad . \quad . \quad (21)$$

(12.2) Description of Experimental Transformer

The rating of the transformer was 1000 kVA 3-phase 19·92 kV/433 volts, star/star connected. It was oil-immersed in a flat open tank so that the leg was horizontally disposed giving easy access to tappings for recurrent-surge-oscillograph tests.

The h.v. winding on each phase comprised 58 disc-type coils each having 16 turns of 0·05 in × 0·28 in copper conductor insulated with a 0·01 in radial thickness of paper. Pressboard spacers were interposed between adjacent discs to provide insulation and oil-cooling ducts. The total height of the h.v. winding stack was 25·7 in, and the transformer-core leg length was 30 in. The core diameter was 10·375 in, and the outside diameter of the l.v. winding, including the surrounding shield, was 12·62 in. The radial clearance between the shield and the inside of the h.v. winding was 0·70 in.

(12.3) Calculation of Winding Constants

(12.3.1) Calculation of Capacitances

The calculation of the inter-turn, inter-section and earth capacitances per section of the uniform winding was made on the lines indicated in Reference 5 and calls for no special comment.

(12.3.2) Calculation of Self-Inductance.

During the impulse test, the l.v. winding is usually short-circuited and earthed except for neutral-current recording resistances and those resistances which limit the voltage rise on non-impulsed terminals. Magnetic flux is excluded from the core for several microseconds and is mainly through air,[16] so that the approximate self-inductance of Section 1 of the h.v. windings will be that of an equivalent rectangular section of width B and depth C adjacent to the l.v. winding and separated from it by a distance d. The l.v. winding is effectively a neutral plane so that the inductance L is given approximately by Grover:[15]

$$L = 0\cdot002\, l_{mt}n^2 \left[\log_\varepsilon \frac{2d}{B+C} + 1\cdot5 + (\log_\varepsilon k - \log_\varepsilon e)\right] \text{microhenrys}$$

where

l_{mt} = Length of mean turn of h.v. winding, cm.
n = Number of turns in the section.
$\log_\varepsilon k$ and $\log_\varepsilon e$ are tabulated for various ratios of B, C and d, and are usually very small.

The justification for using the 'air' inductance lies in the fact that the highest voltage gradients in general occur within the first few microseconds from the commencement of the applied wave.

(12.3.3) Calculation of Mutual Inductances.

Considering section 1 of the winding in relation to section n, the mutual inductance is

$$M_{1-n} \text{ (or } M_{n-1}) = \sqrt{(k_{1-n}k_{n-1}L_1L_n)}$$

where L_1, L_n are the calculated self-inductances and k_{1-n} and k_{n-1} the coupling coefficients of the respective sections. For a uniform winding, the coupling coefficient k_{1-n} is exponential in form. This is because the lines of magnetic flux surrounding section 1 are similar (i.e. analogous) to the electrostatic equipotentials obtained in initial voltage distribution studies (Reference 5, p. 50, Fig. 31).

Hence k_{1-n} = Fraction of flux from section 1 linking section n,

i.e. $$k_{1-n} \text{ or } k_{n-1} = \varepsilon^{-(\alpha x_{1-n})/l}$$

where

l = Height of h.v. winding from the end frame.
x_{1-n} = Distance of section n from section 1.
$\alpha = \sqrt{(C_G/C_S)}$—Reference 5.

For a uniform winding, L_1 and L_n are equal and so also are k_{1-n} and k_{n-1}, but for non-uniform windings they are not.[17] M_{1-n} is, of course, always equal to M_{n-1}. For non-uniform windings, capacitance and self- and mutual-inductance formulae will be derived partly by theory and partly by experiment and measurement with an electrolytic tank. It can be shown that the inverse of the self- and mutual-capacitance matrix obtained from such measurements is equal to the self- and mutual-inductance matrix.

DISCUSSION ON THE ABOVE PAPER

Before a joint meeting of the SUPPLY SECTION *and the* MEASUREMENT AND CONTROL SECTION, 12*th March, and before the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER 25*th February*, 1958.

Mr. E. T. Norris: The main purpose of the paper is to show how the standing-wave theory of impulse voltage distribution, which has been applicable hitherto only to simple uniform windings and rectangular or unit-function waves, can, with the aid of the digital computer, be extended to cover practical non-uniform windings and incoming impulses of any usual form whether full waves or chopped.

Although the authors should be congratulated on this achievement, they have given practical examples only of measurement on simple uniform windings with rectangular waves and have

not thus done justice to their work or to the capabilities of their method. I hope that in their reply to the discussion they will be able to give more practical examples, including the chopped wave calculation shown at the meeting.

Although a digital computer is necessary for a practical analysis of practical windings using the standing-wave method, it is not so for the travelling-wave method. An analysis of stress distribution of engineering accuracy for both full and chopped waves can be obtained longhand in three hours using the travelling-wave method as developed in Reference 7 of the paper. This has the advantage of any longhand calculation that the designer can see what is going on in the course of it and can therefore have a much better appreciation of the factors involved and the internal relations. Moreover, the digital computer can also be used with the travelling-wave method, with corresponding saving in time.

It is, however, doubtful whether for *ad hoc* calculations such as this the time-saving character is important. Considering the high cost of digital computers and the consequent need for their full-time employment, *ad hoc* calculations must generally wait their turn in the queue. Further design work is held up in the meantime, and the delay may well offset time saved in the actual calculation.

The authors' figures for time and cost of computer operation are in their case factual, yet I think both could be reduced under more suitable operating conditions and thus improve their economic case. A price of £89 corresponding to three hours' design work is equivalent to paying a designer a salary of £30000 per annum. I do not think the managing director of any firm would accept either alternative. An hourly rating for computer use, which in the authors' case was, of course, very real, is an arbitrary figure fixed by the owners of computers in the hope that, by and large, and taking one thing with another, they will break even at the end of the year. This rating may meet their immediate purpose, but it is not a good guide as to what a digital computer really does cost.

Although the effect of mutual inductance is shown mathematically in Figs. 5A and 5B, the difference in the electric strength of the insulation for these two waves would not be measurable, and this is typical of practical values. I agree with the authors' criticism of the travelling-wave theory with regard to mutual inductance, but the omission is not of practical importance. Moreover, mutual inductance between turns and coils is in fact an essential part of the travelling-wave theory. Its fundamental principle is that a transformer winding behaves as if the conductors, instead of being bunched into coils, were strung out as a long transmission line. The increase in inductance per unit length caused by the mutual inductance between turns is neutralized by the decrease in capacitance per unit length, so that the velocity of propagation, which depends upon the products of these terms, is unchanged (except for permittivity).

The authors' neglect of losses is not important for the example they have chosen, as the length of winding is comparatively short. For longer windings corresponding to higher-voltage transformers, the attenuation as shown in Figs. 4 and 13 of Reference 7 would be appreciable.

Mr. J. R. Reed: We are currently working along somewhat similar lines to the authors, but are retaining Rudenberg's travelling-wave method for disc-type windings. Both are approximate, and the choice between them must therefore be made on the basis of the results obtained.

We have extended Rudenberg's method to cover the case of chopped waves and obtain results to a good degree of accuracy. We prefer this to the differential-equation method because it gives the voltages between every pair of adjacent discs towards the line end, whereas the authors' method gives fundamentally the voltages to earth and only very limited information on th voltage between adjacent discs, unless the calculation is repeate several times.

We have found it worth while to programme Rudenberg' method for solution by a digital computer. Each solution cost £6 as compared with the £89 that the authors mention.

In our opinion, the differential-equation method is mos useful when the transformer cannot be represented by a simpl ladder network. We then find it preferable to work in terms o branch currents rather than mesh currents. It is necessary t use many more than 40 equations, and we are thinking in term of something over 200. We are tackling this as an eigenvalu problem, and we should be interested to know whether th authors have considered this method of solution.

Mr. E. L. White: Theories have been advanced in whic distributed-mutual-inductance terms appear in the basic equation of oscillations in windings, notably in papers by Pirenne, Helle and Abetti. There is little doubt that mutual inductances shoul be so represented, though the evidence shown in Fig. 5 is uncon vincing. The digital computer could be usefully employed i choosing between the widely differing approximations whic have been suggested for the distribution of mutual inductance.

By introducing an electromagnetic shield inside the h.v winding of their transformer, the authors have ensured that th l.v. winding and the core are both virtually non-existent an hence obtain an exponential mutual-inductance distribution. I a comparable study by Abetti there is no electromagnetic shiel and practically no reduction in mutual inductance with increasin axial separation of turns, yet both papers claim reasonabl agreement with experiment. From oscillographic observation on a small transformer having a turns ratio of unity, we foun that the surge response of the outer winding was almost th same whether all sections or only the terminals of the inne winding were short-circuited, provided that the short-circui connection was earthed. The responses for these two condition were quite different, however, if the inner winding was floating

It seems a possibility, therefore, that the electromagneti shield is not equivalent to a short-circuited secondary windin in the general case, but is, by a fortunate coincidence, analogou for the particular responses investigated by the authors, such a maximum-voltage envelopes, which in any case are somewha insensitive to changes in mutual-inductance distribution.

The soundness and generality of the authors' equivalen circuit should preferably be demonstrated by predicting a wide range of responses, including the frequency spectrum, if th method is to be applied with confidence.

Mr. G. B. Watts (*at Manchester*): Surge problems in trans former windings consist of

(*a*) Voltage distributions for various terminal conditions.
(*b*) Breakdown strengths of insulating media.

(*a*) is mainly mathematical; (*b*) is largely empirical but does n concern us here. In (*a*) allowance has to be made for desig and manufacturing tolerances, and recurrent-surge-oscillograp tests have limited accuracy, so it is exactness of method an technique rather than numerical accuracy which is called for.

The authors deserve praise for considering completely no uniform windings as well as uniform and partially uniform one The non-uniformity can be exaggerated—most windings can b split into groups of similar coils or sections, so that formul and methods can be modified to include non-uniformity. Mor over, the ease of matrix manipulation in computers allov analysis on such windings.

The authors say that travelling wave theory does not allo for precise effects of different waveshapes. For full waves formula quoted by Mr. E. T. Norris is $K_a = 1\cdot 15\epsilon^{-L_T/aT}$ wi

curves for finite wavetail; curves are also known for wavefront corrections. For wavetail chops the effects due to front and chop are usually distinct, and a synthetic fast wave of front equal to the chop is accurate enough.

I notice the authors only used one chopping time (3 microsec) and one time of chop (0·1 microsec). Should they not have varied the former from 3 to 8 microsec and the latter from 0·2 to 1·0 microsec to be practical? They state that any waveshape can be used: for non-analytical functions does this imply Fourier analysis and the Duhamel integral or numerical analysis with polynomial and rational approximations?

Fig. 1A shows all the sections wound spirally outwards, whereas most disc-coil windings spiral inwards and outwards alternately. The former gives a worse voltage distribution than the latter. Assuming equipotential surfaces midway between sections,

$$C_{S,k} = 2[C_{s(k-1,k)} + C_{s(k,k+1)}] \qquad \text{(A)}$$

$$C_{G(k-1,k)} = \tfrac{1}{2}[C_{g,k-1} + C_{g,k}] \qquad \text{(B)}$$

$$C_{G(k,k+1)} = \tfrac{1}{2}[C_{g,k} + C_{g,k+1}] \qquad \text{(C)}$$

Provided that variation from uniformity is small, the authors are

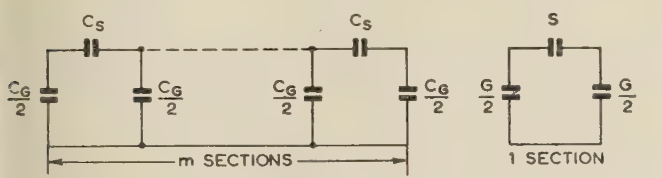

Fig. A

justified in replacing m sections by an equivalent section. Let us suppose m uniform sections replaced as in Fig. A.

If

$$\left.\begin{aligned} \cosh y &= 1 + \frac{2C_S}{C_G} \\ G &= 2\sinh y \tanh(my/2)\,.\,C_S \\ &= \frac{\tanh(my/2)}{\tanh(y/2)} C_G \end{aligned}\right\} \qquad \text{(D)}$$

$$S = \frac{\sinh y}{\sinh my} C_S \qquad \text{(E)}$$

$$\cosh my = 1 + \frac{G}{2S} \qquad \text{(F)}$$

It is easily shown that

$$\frac{\tanh(my/2)}{\tanh(y/2)} < m$$

and

$$\frac{\sinh y}{\sinh my} < \frac{1}{m}$$

For most disc-coil windings, $0{\cdot}1 \leqslant y \leqslant 0{\cdot}2$. With $m = 10$ and $y = 0{\cdot}1$, tanh 0·5/tanh 0·05 = 9·25, and sinh 0·1/sinh 1 = 0·0852; and with $m = 10$ and $y = 0{\cdot}2$, tanh 1/tanh 0·1 = 7·64, and sinh 0·2/sinh 2 = 0·0697. These figures show the care to be exercised in lumping network parameters.

In view of the authors' stressing the greater accuracy of lumped parameters, their lack of adverse comment on the formula $\alpha = \sqrt{(C_G/C_S)}$ is surprising since it is based upon distributed parameters. Surely the fundamental parameter is y where $\cosh y = 1 + (C_G/2C_S)$, C_G and C_S being sectional earth and series capacitances in a uniform winding. A non-uniform winding would have a y for each section. The principle is that y is essentially a lumped network parameter.

Inclusion of mutual inductances means that the normal chain-equations of ladder networks are inadequate and recourse to matrices is inevitable excepting initial distributions for $1(t)$. However, designers are mostly interested in maximum values of intersection voltages—knowledge of initial and final distributions usually suffices.

If Y_k is the input capacitance from the neutral end of section k, the voltage equations are

$$\frac{V_k}{V_{k-1}} = \frac{C_{s,k}}{C_{s,k} + Y_k} \qquad \text{(G)}$$

$$Y_{k-1} = C_{G(k-1,k)} + \frac{C_{s,k} Y_k}{C_{s,k} + Y_k} = C_{G,(k-1,k)} + \frac{V_k}{V_{k-1}} Y_k \qquad \text{(H)}$$

so that

$$\frac{V_k}{V_0} = \frac{V_k}{V_{k-1}} \frac{V_{k-1}}{V_{k-2}} \cdots \frac{V_3}{V_2} \frac{V_2}{V_1} \frac{V_1}{V_0} \qquad \text{(J)}$$

These equations should be easily programmed for a large number of voltages. It should be noted that the authors' Q-matrix involves several zero constants in the storage locations.

For evaluating A_{jk}^{-1} one assumes that $|A_{jk}| \neq 0$ and the matrix such that $|A_{jk}| \nless$ the smallest number held in the computer.

The authors appear to adhere to the standing-wave technique and claim 2 h 13 min as the time for their calculations; this is little less than the time required for calculating voltage distribution and intersection strength longhand by the travelling wave technique. With the computer the latter would surely be the faster method.

Given two adjacent groups made up of similar sections, the first with n, the second with n', turns per section with m sections in the first, if X_T, X_C are the space constants for the turn and section standing distributions with $H = \pi X_C$ the travelling wave headlength, $t = \epsilon^{-n/X_T}$, $t' = \epsilon^{-n'/X_T}$, $u = \epsilon^{-n/X_C}$, $u' = \epsilon^{-n'/X_C}$, v_k = voltage across section k, $v_{k,k+1} = v_k + v_{k+1}$ = voltage across sections k, $k+1$,

$$\begin{aligned} v_1 &= a_T + a_C + a_w, & v_{1,2} &= (1+t)a_T + (1+u)a_C + 2a_w, \\ v_2 &= t a_T + u a_C + a_w & v_{2,3} &= t(1+t)a_T + u(1+u)a_C + 2a_w \\ &\cdots & &\cdots \\ v_k &= t^{k-1}a_T + u^{k-1}a_C + a_w, & v_{k,k+1} &= t^{k-1}(1+t)a_T \\ v_{k+1} &= t^k a_T + u^k a_C + a_w & &\quad + u^{k-1}(1+u)a_C + 2a_w \\ &\cdots & &\cdots \\ v_m &= t^{m-1}a_T + u^{m-1}a_C + a_w & v_{m-1,m} &= t^{m-2}(1+t)a_T \\ & & &\quad + u^{m-2}(1+u)a_C + 2a_w \end{aligned}$$

where $a_w = \dfrac{n}{H_C}$

Now, if $$a_{T'} = t^m \frac{1-t'}{1-t} a_T,\ a_{C'} = u^m \frac{1-u'}{1-u} a_C,\ a_{w'} = \frac{n'}{n} a_w \qquad \text{(K)}$$

then

$$v_{0,1'} = v_k + v_1' = (t^{m-1}a_T + u^{m-1}a_C + a_w) + (a_{T'} + a_{C'} + a_{w'})$$

i.e.

$$v_{0,1'} = \left[\frac{t^{m-1}(1-tt')}{1-t}\right] a_T + \left[\frac{u^{m-1}(1-uu')}{1-u}\right] a_C + \left(\frac{n+n'}{n}\right) a_w \qquad \text{(L)}$$

Also, $$v_{1,2'} = (1 + t')a_{T'} + (1 + u')a_{C'} + 2a_{w'}$$

i.e. $$v_{1,2'} = \left[\frac{t^m(1 - t'^2)}{1 - t}\right]a_T + \left[\frac{u^m(1 - u'^2)}{1 - u}\right]a_C + \frac{2n'}{n}a_w \quad \text{(M)}$$

Surge strengths are usually more important than surge voltages, the weak places being group beginnings and junctions due to change in insulation and/or turns. Thus for a first check many intersection voltages can be ignored and jumps from group to group and tests for weak places done by eqns. (K), (L) and (M), which can be easily programmed for the computer.

Mr. L. C. Richards (*at Manchester*): The authors have used a single isolated winding divided into 20 circuit divisions, which appears to give a fairly accurate picture of the inter-coil stresses and voltages to earth on both full and chopped waves. There should be no fundamental difficulty in including the effects of coupled windings (i.e. the effect of the presence of the l.v. winding during an impulse test on the h.v. winding) and also including attenuation effects in the winding by using small series resistances with each section. These would form worthwhile studies.

It is extremely interesting to note that the effect of chopped waves can be calculated. I think this is the first time that such a claim has been made, and it is most important, since chopped waves give rise to high intersection voltages and can be a frequent source of trouble to the designer.

The authors deal only with the straight-section type of winding, but many other arrangements are in use. Transformers are built with sandwich windings of the core or shell construction; with a limited number of layer windings for large high-voltage transformers; and with a multi-layer, multi-turn per layer arrangement for small distribution transformers. Also, of course, there are numerous arrangements of 3-winding transformers, and there is the study of the effect on a l.v. winding of an impulse voltage or surge applied to an h.v. winding. I should like to know if the authors consider that the method described will deal with all these cases.

Mr. A. S. Husbands (*at Manchester*): The method of calculation has the practical merit that it is able to deal with unequal divisions of the h.v. winding, and this ability is particularly useful in assessing the intersection voltages at and near the line end. In many cases the simpler determination of the initial voltage distribution provides a sufficient guide to the intersection and inter-turn voltages at the line end. However, in large transformers the true initial voltage distributions may not be realized in practice, even with chopped waves, because some of the natural periods of oscillation are very short. In that event the estimates of inter-turn and inter-section voltages would be pessimistic when they were based on the initial voltage distribution. The authors' method would give the correct distributions for given applied waves, provided the subdivisions were small enough at the line end of the winding.

The authors state that the end-fringing capacitance of the h.v. winding has little effect on the voltage across their first division. However, the first division of the winding consists of three sections, and the end capacitance may be expected to have little effect over this rather large division. The effect within the first section would be considerable, and is the reason for fitting an electrostatic end-ring.

The method of determining the mutual inductance between parts of the h.v. winding is simple and ingenious, but it depends on the assumption that magnetic flux does not penetrate inside the l.v. winding (or inside a metal cylinder in the example quoted). However, it is the cylinder or the l.v. winding which prevents or reduces the flux penetration, since they are closely coupled to the h.v. winding. This relatively large mutual inductance is taken into account by the authors by assuming a limiting condition of a restricted field boundary, so that the lower values of L and M for the h.v. winding are effective values to compensate for the overall effect. The effective values will be lower than the true values of L and M, and the authors' method is correct only when the l.v. winding is a continuous short-circuited cylinder of negligible impedance. The true influence of the l.v. winding and the events occurring in that winding

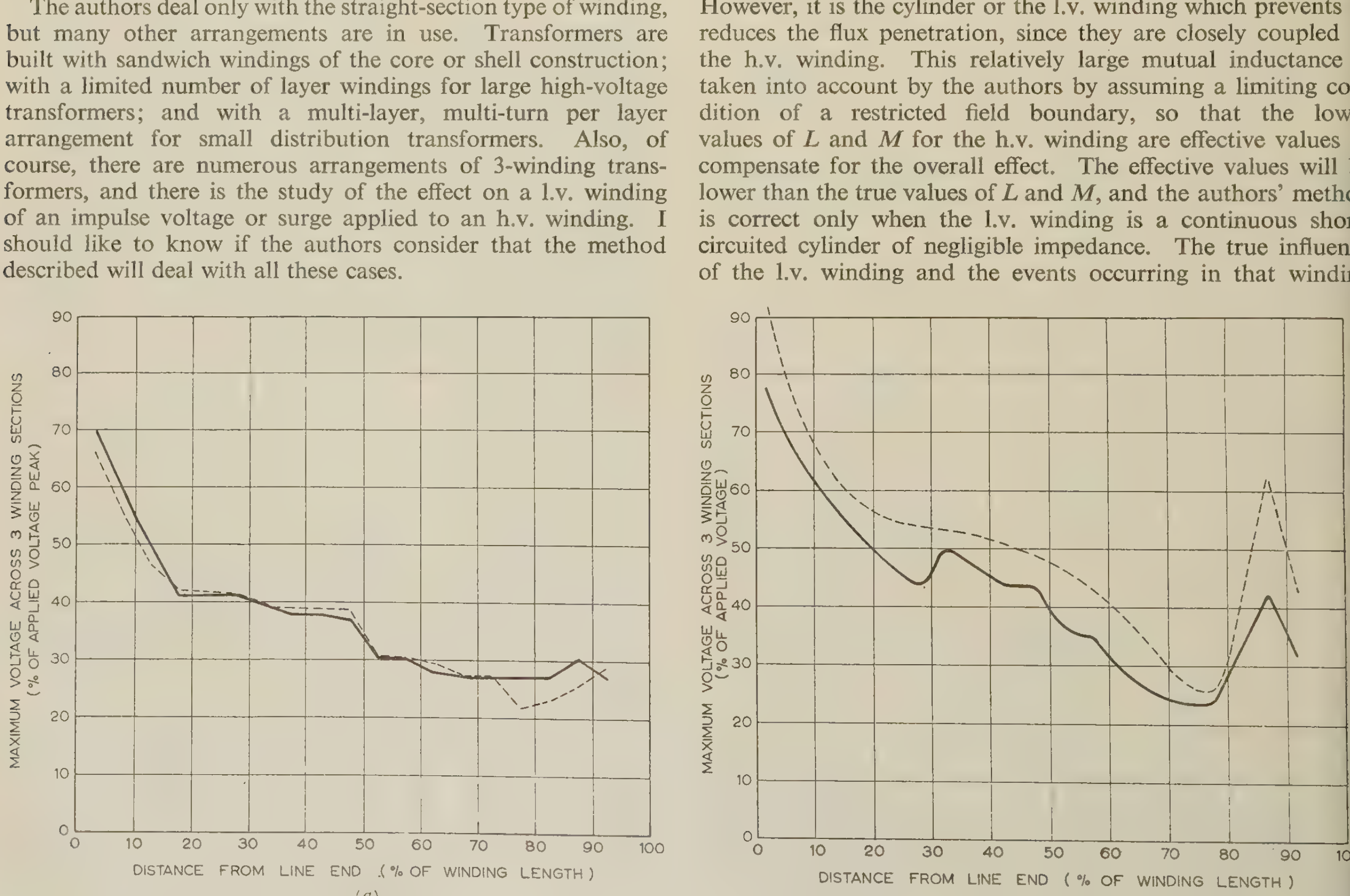

Fig. B.—Maximum intersection voltages.

(*a*) Full wave.
(*b*) Chopped wave.

—— Recurrent-surge oscillograph measurements.
– – – Calculated results.

itself could be evaluated only by introducing the mutual inductances and capacitances between the h.v. and l.v. windings. This would increase the number of circuit loops in each division of the equivalent circuit. Could the authors' methods include the extra complication?

In the same connection it should be noted that the true self- and mutual-inductances are independent of time, but the effective values appear to vary because of the neglect of the true mutual inductance between the h.v. and l.v. windings.

Miss B. M. Dent, Mr. E. R. Hartill and **Mr. J. G. Miles** (*in reply*): Mr. Norris and several other contributors draw attention to the high apparent cost of the method described as compared with that of a longhand travelling-wave analysis. The cost quoted, which is unavoidably based on rental charges since no other figures were available, covers the calculation and printing of all voltages to earth over the entire period. Though desirable for investigational purposes, this procedure is unnecessary for routine design when voltage maxima alone are of interest. By printing out only selected voltages and by the use of the faster computers now available, together with the modified method of computation suggested by Professor Hartree, the cost per calculation reduces to the order of £2. This compares favourably with the figure of £6 quoted by Mr. Reed for a travelling-wave calculation.

However, the main purpose of the present method was not to elaborate the solution of windings for which a travelling-wave analysis is adequate, but to provide a basis for the solution of more complicated problems which cannot be tackled by existing methods. The flexibility of the equivalent-circuit approach coupled with the great power of present-day computers makes the extension of the present method to the representation of coupled windings completely feasible.

Messrs. White and Husbands rightly stress the importance of the l.v. winding in this respect. Moreover, the generality of the method makes it particularly suitable for the comparative evaluation of various assumptions in the winding representation, as suggested by Mr. White in connection with mutual inductances.

Mr. Norris and Mr. Richards refer to the importance of calculations for chopped waves. Fig. B shows results obtained with the present method for a 0·1/50 wave chopped at 3 microsec compared with the full-wave results.

In reply to Mr. Watts, if the applied voltage is a non-analytical function of the time t, its value, for all values of t required by the integration process, must either be fed directly into the computer or be computed by it. When the latter course is preferred, a polynomial fitted to the given data is easy to programme and economical of machine time, but any formula representing the data by means of computable functions could be used.

In view of the complications involved, we have not considered using the eigenvalue method of solution mentioned by Mr. Reed, and we shall be most interested to hear how it works out in practice.

DISCUSSION ON

'A DEEP ELECTROLYTIC TANK FOR THE SOLUTION OF 2- AND 3-DIMENSIONAL FIELD PROBLEMS IN ENGINEERING'*

BEFORE THE NORTH-WESTERN MEASUREMENT AND CONTROL GROUP AT MANCHESTER, 22ND OCTOBER, 1957

Mr. H. Diggle: The paper follows on from that presented by Mr. Hartill and myself† a few years ago which dealt with a tank primarily for 2-dimensional studies and the wedge technique for problems of circular symmetry, such as bushings of composite dielectrics. Very little has been published about deep tanks which enable 3-dimensional studies to be made by plotting at different levels. The electronic method of pulse excitation and measurement which are described overcome polarization problems, and give very accurate detection of the null-balance positions. Since the main object of the deep tank is for 3-dimensional studies, it is regrettable that several of the examples described in the paper are 2-dimensional, and do not necessarily involve the use of a deep tank.

Automatic means of plotting have been suggested, involving the use of two motor-operated mechanisms working at right-angles to each other; but in my view this is not worth while, since the time of plotting is only a very small proportion of that spent on a complete study of any particular problem.

While this tank provides facilities for the solution of many problems which can be very tedious by other methods, such as relaxation, it is not claimed to be the best for all classes of problem. One weakness which has still to be overcome is some method of representation of different permittivities in 3-dimensional studies.

Tap water is stated to be generally suitable, but some information would be useful as to the methods the authors have found most convenient when improved conductivity is necessary.

Dr. C. W. Miller: The logical arrangement of the paper masks to some extent both the technical novelties introduced and also some of the difficulties overcome. The novelties can be emphasized in a brief account of why and how the equipment was developed. It was, in fact, produced to deal with a specific problem, that of the field distribution in the proton linear accelerator described in Section 5.2. It was necessary to know to a high degree of accuracy both the axial and radial gradients in the gaps between the drift tubes, so that this information could be fed to an analogue computer† and thus the beam-dynamics problems of the accelerator as a whole could eventually be solved. It was clear that some form of electrolytic tank would be required, and the well-known wedge tank was first considered, since the problems could be reduced to two dimensions because of the circular symmetry about the longitudinal axis. Unfortunately, the greatest accuracy in field measurements was required at points on the axis, and this is where the wedge tank, having zero depth of electrolyte, gives little, if any, accuracy.

The suggestion was therefore made—originally, I believe, by Mr. Crowley-Milling—that a deep tank should be used. It is worth stressing that the deep tank was required to obtain

HARTILL, E. R., MCQUEEN, J. G., and ROBSON, P. N.: Paper No. 2179 M, October, 1956 (see 104 A, p. 401).
DIGGLE, H., and HARTILL, E. R.: 'Some Applications of the Electrolytic Tank to Engineering Design Problems', *Proceedings I.E.E.*, Paper No. 1627 M, February, 1954 (101, Part II, p. 349).

† CROWLEY-MILLING, M. C.: 'An Analogue Computer for Solving the Equations of Motion in Particle Accelerators', *Journées Internationales de Calcul Analogique*, 1956, p. 257.

accuracy along the axis, and no question of 3-dimensional problems was at that time considered. The accuracy required meant that the models of the drift tubes would have to be four times actual size and that the greatest care in mechanical arrangements of plotting would have to be taken. At this stage Mr. Hartill undertook the provision of the very large deep tank and the necessary plotting facilities. Since gradients rather than potentials were required, the 2-probe method previously used by Sander and Yates was adopted, although some development of the probe was expected. A.C. or pulse measuring equipment was required and, if possible, this had to have greater accuracy than had been previously obtained. That this problem was solved can be seen from the elegant electronic arrangements developed by Mr. McQueen.

Various difficulties were encountered, and some of these, e.g. polarization effects and the splitting of wooden models, are described, but were eventually overcome by the use of metallic spinnings. An extensive plotting programme was undertaken by Mr. Robson, in collaboration with Mr. T. R. Jarvis, and fields were determined in 110 different drift-tube gaps. This work took several months, and was followed by extensive rounding and interpolation programmes carried out by Mr. Jarvis to provide information for the analogue computer.

The computer programme itself was an extended one, but eventually the dynamics problems were solved and operating information for an accelerator was obtained. It is of interest that this accelerator, partially described in the paper, is now nearing completion and the success of its operation at Harwell will perhaps give practical proof of the value of the electrolytic-tank plottings.

Mr. E. Elliott: My own experience is with an electrolytic tank only 4–6 in deep. The authors mention their use of Bakelite board, sometimes brass sprayed, when representing conducting surfaces. This material has often been used in my own models in a different manner, i.e. to produce depth changes in multi-dielectric models by fixing sheets in appropriate places in the cork-lined bottom of a wooden tray. These boards have shown a marked tendency to warp unless screwed to the bottom of the tray (with the screw heads insulated, of course). Although these models are somewhat smaller than those of the authors, the relative dimensions of Bakelite are not dissimilar, being about 2 ft × 1 ft × $\frac{1}{4}$ in; have the authors experienced any trouble in this respect and what measures would they adopt in that event? The variations in Bakelite board mentioned I assume to be surface undulations.

The authors also state that equipotentials with a positional accuracy of about 1% are sufficient for general work. With a tank of the size quoted, which would cater for a model about 50 in long, this accuracy means that equipotentials can be as much as $\frac{1}{2}$ in in error. Using a smaller tank, 3 ft × 2 ft × 4 in deep, I find an accuracy of $\pm 0 \cdot 01$ in is possible, which represents a positional accuracy of 0·0833%.

With regard to the insulator-string example, I assume from the drawing of the model given in the paper that the effect of conductors above or below the string has been neglected. Fig. B shows estimates of what one might expect these effects to be on the field distribution. The full lines are copied from the field plot given in the paper and the broken ones are the equipotentials estimated from the plot, assuming that in 3-phase operation when one line is 100% positive, the one above or below may be 5% negative with respect to earth instantaneously. Fig. B(ii) shows that a conductor above will have some effect upon the distribution over the insulator string. Whether this effect is significant can be judged only by further investigation, but it may well be that the authors have already considered this point.

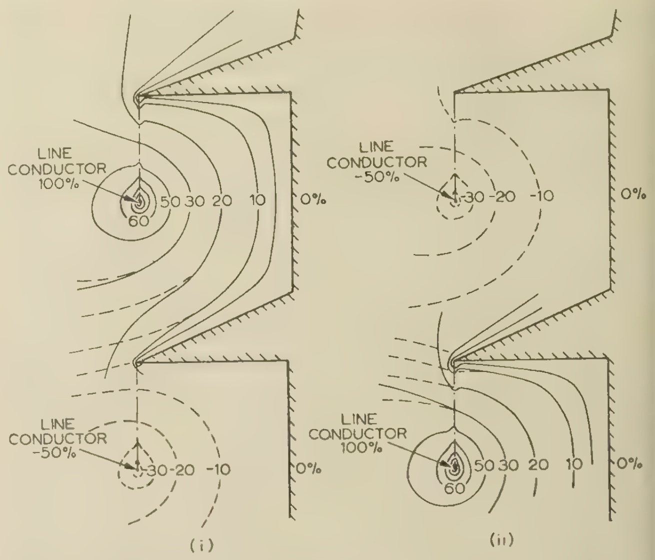

Fig. B.—Equipotentials around insulator string with suspended conductors.

The paper states that the water is changed every 3 days, and very frequent changing is obviously impracticable with such a large volume. But I have observed quite a lot of atmospheric particles collected on the water surface in less than 3 days, and should be interested to know whether the authors experience any difficulty from this.

Messrs. E. R. Hartill, J. G. McQueen and **P. N. Robson** (*in reply*): In reply to Mr. Diggle's query on low-conductivity electrolytes, we have found that a dilute solution of sodium sulphate is the most suitable. It does not attack the electrodes in the same way that sulphuric acid does, and it seems to give the least change in conductivity with time and temperature.

Dr. Miller gives the historical background of the equipment, which has since been in almost continuous use for solving a wide variety of problems originating both in our own and from outside organizations.

Mr. Elliott mentions the warping of the Bakelite boards used in models. We have generally used several thicknesses of board bolted together and subsequently varnished. In some cases we have used Araldite as a seal, and under these conditions we have not experienced any warping.

Although we have stated that positional accuracies of 1% are sufficient for general work, the equipment is capable of 0·01%. We have therefore not experienced the large discrepancies of $\frac{1}{2}$ in between equipotentials mentioned by Mr. Elliot, although discrepancies of about $\frac{1}{8}$ in sometimes occur in the very weak fields which are obtained near the tank boundaries. Also, for a given design of measuring equipment, the larger the tank and model the greater is the accuracy obtained.

Mr. Elliott is correct in assuming that the effects of the conductors above and below the insulator string have been neglected. His diagram illustrates the estimated effects, but it is significant that the distribution across the string is substantially unchanged. The reasonably good agreement between the tank results and those on the insulator string confirm that the effect is small.

During the rather precise proton-accelerator measurements we noticed that dust sometimes collected on the surface of the electrolyte. Removing the dust by skimming the surface, or by introducing a drop of detergent at the centre of the model had no measurable effect.

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Jan. 1958

THE USE OF STEEL-TANK MERCURY-ARC INVERTERS FOR GENERATING MEDIUM FREQUENCIES FOR INDUCTION HEATING

By D. L. SMART, B.Sc.Tech., and J. J. L. WEAVER, Associate Members.

(*The paper was first received* 6*th August, and in revised form* 30*th September*, 1957. *It was published in January*, 1958, *and was read before the* UTILIZATION SECTION 13*th March, the* NORTH-WESTERN UTILIZATION GROUP 18*th March, and the* SHEFFIELD SUB-CENTRE 16*th April*, 1958.)

SUMMARY

The paper presents in a non-mathematical way a general survey of the circuit operation and construction of 6-anode steel-tank mercury-arc inverters for the generation of medium-frequency power, in the output range up to 250 kW at 1–2 kc/s.

The basic operation of the inverter circuit is first described, together with some features of practical inverter circuits, including the problem of starting inversion without modifying or previously exciting the tuned output circuit. The characteristics and limitations of the inverter valve and other main-circuit components are discussed, together with the requirements of different types of melting and billet-heating furnaces.

The problem of designing circuits to meet all the varied control requirements has been met by the development of an electronic grid-control unit, which ensures reliable starting and gives facilities for automatic frequency and voltage control.

A general description is given of installations in service for forge heating and melting.

(1) INTRODUCTION

Supplies of power for induction heating in the medium-frequency range between 50 and 10 000 c/s are normally obtained from motor-alternator sets. The theoretical possibility of generating a range of these frequencies up to 1–2 kc/s by mercury-arc inverters has long been recognized, and earlier experimental work was done on the Continent and in the United States, followed by the installation of a few equipments for the supply of power to induction melting furnaces.[1]

The advantages of the mercury-arc inverter are that it is more efficient than a motor-alternator set, it is static, and its output frequency can be easily varied to match changes in the load circuit tuning. There are, however, two major difficulties in the development of inverters for high powers and for general application. These are the design and operation in a full-scale circuit of a suitable inverter valve, and the design of control circuits, and both these problems are discussed in some detail in later Sections of the paper.

One important condition which determined the basic form of the control circuits described is the achievement of reliable and automatic starting of the inverter without the use of heavy-current contactors or other means of modifying the main load circuit characteristics during starting.

(2) THE INVERTER CIRCUIT

(2.1) Basic Operation of the Bi-Phase Inverter

Fig. 1 shows a 2-anode mercury-arc valve in the basic inverter circuit. The steady-state operation of this circuit is shown in Fig. 2, where it is assumed that the d.c. reactor ensures a steady direct current in the cathode, with negligible ripple, and that a sinusoidal voltage is maintained across the inverter transformer output terminals PQ by the oscillation of the load coil and capacitor.

Mr. Smart was, and Mr. Weaver is, with the English Electric Co. Ltd.

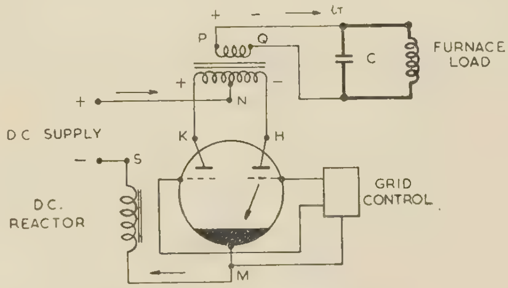


Fig. 1.—Bi-phase inverter circuit.

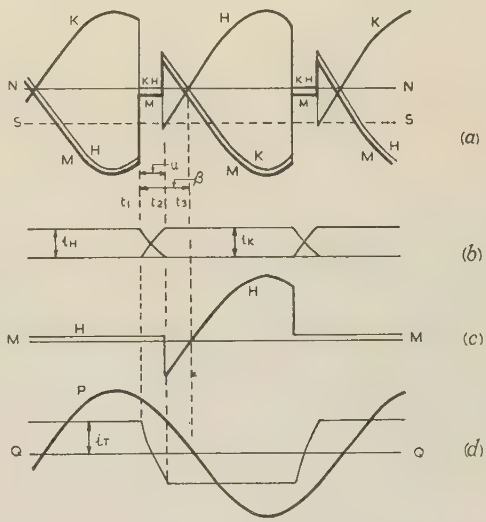


Fig. 2.—Bi-phase inverter waveshapes.

(*a*) Anode and cathode potentials to neutral.
(*b*) Anode currents.
(*c*) Anode potential to cathode.
(*d*) Output potential and current.

In the first half-cycle shown (in which the transformer voltages have the polarities shown in Fig. 1) anode H is firing, and anode K, which is at a high positive voltage to cathode, is prevented from firing by grid control. The transformer winding currents are in the directions N to H and Q to P, and there is thus a flow of power into the load circuit. At a time t_1, anode K is allowed to fire, and the current commutates (with the primary winding effectively short-circuited) from anode H to anode K in time t_1 to t_2 (phase angle u), because of the voltage maintained across the transformer secondary winding by the oscillating load circuit. After commutation is complete at time t_2, the current is carried by anode K only, until the reverse commutation takes place half a cycle later.

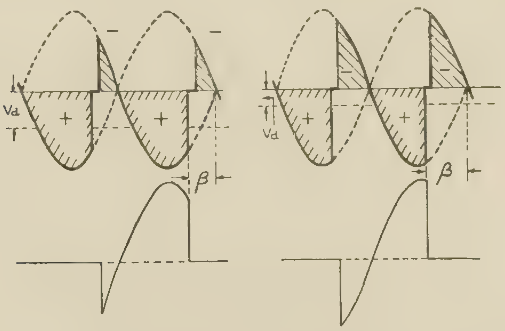
Fig. 2(c) shows that the potential of anode H is negative with respect to cathode from t_2 to t_3, and the deionization in the

anode/grid region must then be sufficiently complete for the grid to prevent the anode re-firing at t_3.

As shown in Fig. 2(a), the average potential of the cathode M is negative with respect to the neutral point N, giving a back-e.m.f. in the d.c. circuit (the ripple voltage MS being absorbed in the d.c. reactor).

The value of the sinusoidal voltage across the load circuit is, of course, not fixed, but reaches an equilibrium value at which the back-e.m.f. is equal to the applied direct voltage (neglecting voltage drops). Thus, with a fixed firing angle β, and a fixed load impedance, the output voltage (and hence the input and output currents) will vary in proportion to the direct input voltage.

An alternative method of varying the output voltage is by varying the firing angle β. Fig. 3 shows how an increase in β



(a) (b)

Fig. 3.—Direct voltage and anode-cathode voltage.

(a) $\beta = 50°$, $u = 15°$, $V_d = 0{\cdot}65 V_0$.
(b) $\beta = 75°$, $u = 11°$, $V_d = 0{\cdot}31 V_0$.

effectively reduces the proportion of alternating output voltage appearing as a back-e.m.f. in the d.c. circuit, and if the direct supply voltage is fixed the output voltage must increase to restore the back-e.m.f. to its previous value.

In this case, the poor power factor of the transformer [(Fig. 2(d) shows that increase in β will give increased phase displacement between output current and voltage] and the poor utilization of the inverter valve (due to low ratio of V_d to m.f. anode voltage) will result in both these items having high current and voltage ratings for the power being delivered. This method of voltage variation is thus only economic over a very limited range.

(2.2) The Cyclo-Inverter

The high-power m.f. inverters so far developed have usually been of the type known as cyclo-inverters, where 3-phase power is used as the input supply for a set of three bi-phase inverters without preliminary rectification.[1, 2] Fig. 4 shows the basic circuit of this arrangement using a simple self-excited grid circuit. Current flows from the l.f. phase whose potential is most positive at any instant, to feed its associated inverter circuit. As all three inverter circuits are connected to similar windings on a common output transformer, and supplied with grid control impulses from a common grid supply system, they all have effectively the same back-e.m.f., and no current can flow in the other l.f. phases. Thus, each phase winding and its associated m.f. winding and pair of anodes carry current for about one-third of each supply-frequency cycle, with short commutating periods during which two phases and their inverter circuits are operating in parallel.

By modifying the grid circuit so that the m.f. grid-firing pulses on a pair of grids are suppressed at the time when the associated pair of anodes would normally start to conduct, the period of operation in any phase can be delayed to any desired extent, and

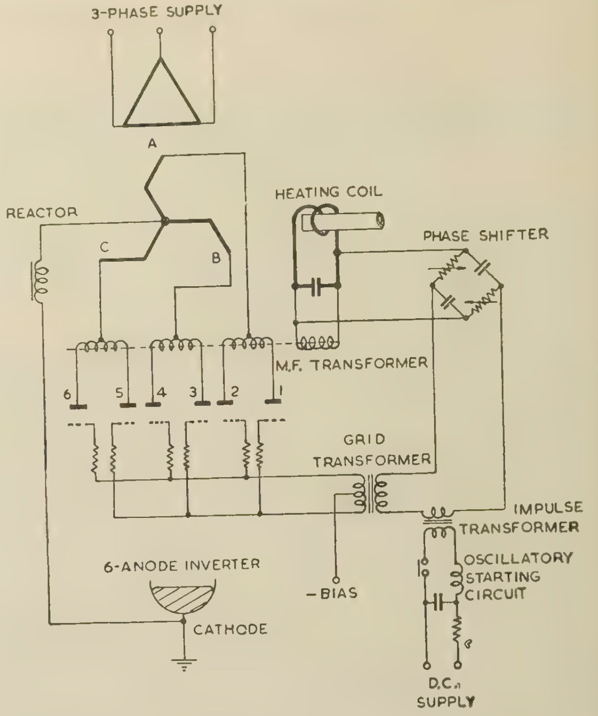


Fig. 4.—Simplified circuit diagram of m.f. inverter.

the average voltage supplied to the circuit during the conducting period is thus reduced in exactly the same way as for a 3-phase grid-controlled rectifier. The size of d.c. reactor used must be sufficient to reduce the amount of third-harmonic ripple in the cathode current to the value required.

The operation of the whole circuit can best be understood by reference to the waveshapes drawn out for the various parts of the circuit in Fig. 5, where, for clarity, a fairly low output frequency is shown.

(2.3) The Practical Inverter Circuit

(2.3.1) The Starting of Inverter Action.

In practice, great difficulty was found in early experiments in starting the inverter action without modifying the output circuit, e.g. by introducing additional series resistance. If we assume that anode H is fired to initiate the first half-cycle of operation of the circuit of Fig. 1, the current will rise approximately linearly from zero, and commence charging the capacitor C. If starting is to be successful, anode K must not be fired until there is sufficient charge in the capacitor to reverse the current in the transformer windings, and thus reduce the current in anode H to zero. If, however, anode K is fired too late, the capacitor will have been discharged again by the rising current in the load coil. A full analysis shows that starting is only possible if the transformer leakage reactance is less than a certain fraction of the load-coil inductance, and that the interval between firing anodes H and K must be much less than at the normal operating frequency. On subsequent half-cycles, commutation is much easier, for two reasons:

(a) In the first half-cycle the rising current in the load inductance is fully asymmetrical, i.e. always in a direction to discharge the capacitor, whereas in normal operation the load-coil current starts each half-cycle in a direction to charge the capacitor, and only reverses shortly before the next anode is fired.

(b) In the first half-cycle the current rises linearly from zero, and

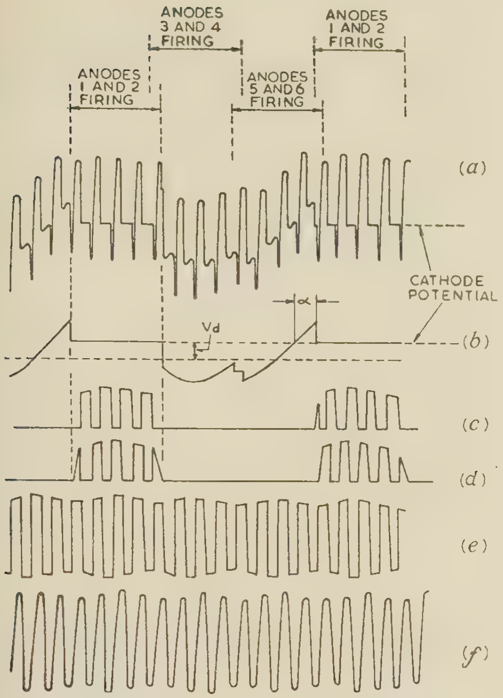


Fig. 5.—Cyclo-inverter waveforms (circuit in Fig. 4).

(*a*) Voltage of anode 1.
(*b*) Low-frequency components of (*a*).
(*c*) Current in anode 1.
(*d*) Current in anode 2.
(*e*) Output current—note variation due to d.c. ripple.
(*f*) Output voltage.

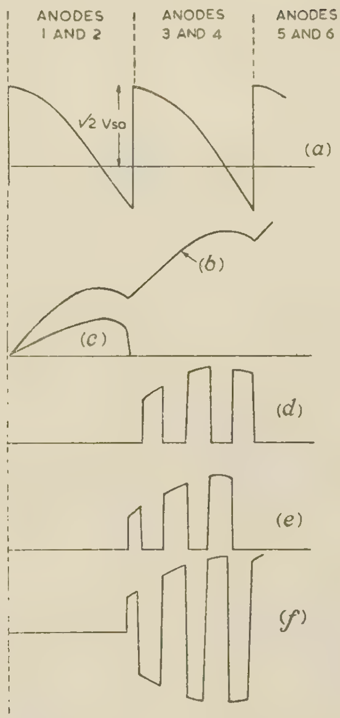


Fig. 6.—Starting of cyclo-inverter.

(*a*) Effective input voltage.
(*b*) Cathode current.
(*c*) Current in anodes 1 and 2.
(*d*) Current in anode 4.
(*e*) Current in anode 3.
(*f*) Output current.

thus at any instant is equal to twice its average value since the start, i.e. the current to be commutated is twice the average capacitor-charging current; whereas in later half-cycles the proportionate increase in current is much less.

Fortunately, the difficulty experienced in the first half-cycle may be largely avoided in a cyclo-inverter by suitable grid control, as shown by the waveshapes in Fig. 6. In this system the effective input voltage is reduced by grid control at supply frequency; the inverting action is allowed to fail for the first pair of anodes, which thus both carry current in parallel, with no voltage appearing across the output transformer. Owing to the large cathode reactor, the current only rises to a proportion of full load, and when the first of the next pair of anodes fires, the large voltage between supply phases (because firing is delayed by grid control) ensures a very rapid transfer of this current from anodes 1 and 2 to anode 3. The average capacitor-charging current during the m.f. half-cycle until anode 4 is allowed to fire is thus almost equal to the current to be commutated, and starting is possible with a less favourable ratio of transformer reactance to load inductance. An oscillogram of this starting action is shown in Fig. 7.

For any given input current, there will be a delay of a few m.f. cycles before the oscillatory energy in the output circuit (and hence the available m.f. commutating voltage) can build up its steady value. Hence, immediately after starting and while the input current is rising rapidly, the m.f. commutating time (u in Fig. 2) will be larger than under steady conditions, and the anode firing angle β must therefore be increased to maintain safe deionizing times. On the other hand, this earlier firing must not continue until a steady state is reached, as this will result in an excessive output voltage as shown in connection with Fig. 3(*b*). The grid control circuit is therefore arranged

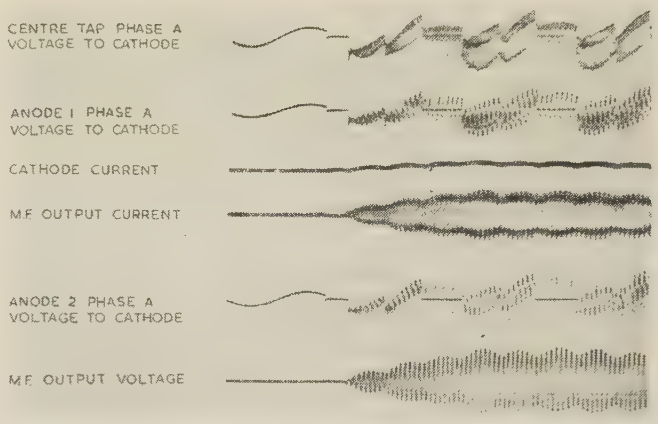


Fig. 7.—Oscillogram of starting action.

to give a gradual transition from an early m.f. firing time to normal firing during the first cycle or two of supply frequency, as described in Section 5.

(2.3.2) **Output Voltage and Power Factor.**

The inverter output consists of an approximately square-wave current which leads the output voltage by an angle of very nearly $\beta - \frac{1}{2}u$ [Fig. 2(*d*)], and which affects the tuned output circuit in two ways:

(*a*) The leading reactive component of this current must be absorbed by the output capacitor, which must therefore be increased by perhaps 20% above the value required to correct the load-coil power factor to unity; i.e. the inverter works at about 10% higher

frequency than the natural resonant frequency of load and capacitor. An increase in β will thus increase this reactive component and cause the output circuit to oscillate at a still higher frequency.

(*b*) The effect of the harmonics in the inverter output current is to increase the r.m.s. current carried by the capacitors slightly above the value calculated on a sine-wave basis, and to cause some distortion of the output-voltage waveform. The total amount of harmonic voltage distortion with practical values of inverter and load power factor is, however, unlikely to exceed about 10%, and a design theory based on a sinusoidal output voltage is thus satisfactory for determining normal operating conditions.[1]

(2.3.3) Commutation Effects.

At the end of each m.f. commutation the recovery voltage across the m.f. transformer primary winding, and consequently also between the outgoing anode and the firing anode, has superimposed on it an oscillation developed in the leakage reactance and stray capacitances of the transformers and reactor. This oscillation is in the range of 10–50 kc/s, and usually continues for an appreciable fraction of the m.f. cycle.

The resultant voltage between the outgoing anode and cathode is shown in Fig. 8(*a*), and the effective deionizing time allowed

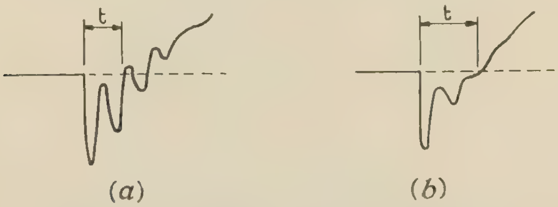


Fig. 8.—Anode-voltage waveshape showing available deionizing time, *t*.

(*a*) Without damping filters.
(*b*) With damping filters.

may be considerably less than the calculated value. Damping circuits consisting of capacitors and series resistors are therefore connected from cathode to the centre tap of each m.f. primary winding (points A, B and C in Fig. 4), so that a damping circuit is always effectively connected across one half of the m.f. winding which is operating at the time. This reduces the oscillations to the proportions shown in Fig. 8(*b*).

Another effect is caused by a small current consisting of harmonics of the medium frequency which may be reflected through the supply frequency transformer into the supply and cause local harmonic voltage distortion. This effect can be completely suppressed by connecting a 3-phase power-factor-correction capacitor of about one-tenth of the inverter output rating across the primary lines.

(3) THE INVERTER VALVE

As will be seen later in this Section, there are four main requirements of a high-power m.f. inverter valve:

(*a*) Suitable current and peak voltage ratings.
(*b*) A very short grid-control recovery time.
(*c*) Ability to operate without backfiring at a high commutation factor.
(*d*) Ease of control.

As it was considered that these requirements would be easier to achieve in a valve using comparatively low currents and correspondingly high voltages, the design of valve used by the authors was based on a high-voltage (30 kV peak inverse) sealed steel-tank rectifier previously developed for broadcast transmitter supplies.[4] The more detailed studies of requirements given below, and discussion of design features, are therefore related particularly to this design of valve.

(3.1) Current and Peak Voltage Ratings

The current I_d flows continuously in the cathode and inverter tank and appears in each anode arm for periods totalling one-sixth of each supply-frequency cycle; it can therefore be regarded as having the same heating effect as the same direct current in a 6-phase rectifier.

In a bi-phase inverter, where V_d is typically $0 \cdot 65 V_0$, the forward peak anode voltage is nominally $2\sqrt{2}V_0$ [see Fig. 2(*a*)] or $4 \cdot 4 V_d$. In a cyclo-inverter the peak forward and inverse voltages are increased by the addition of the l.f. components and usually occur on anodes of the non-conducting phases.

When working with a large value of β and a large angle of input phase delay, peak values are found (including overswing) of up to 8·5 times the nominal value of V_d (i.e. the value produced by using the supply transformer to feed a 3-phase rectifier).

This means, for example, that a valve capable of operating with peak anode voltages of 30 kV can be used with values of V_d up to about 3·5 kV. The input power to the circuit is $V_d I_d$, and thus if the rated cathode current is 80 amp, the inverter output power from this valve after allowing for losses would be about 250 kW.

(3.2) Grid-Control Recovery Time

The deionizing time allowed before the anode again becomes positive [$(\beta - u)$ in Fig. 2(*a*)] must include the time required by the grid to regain control, plus a small safety margin. In Figs. 3(*a*) and 3(*b*) this total period is 35° and 64° respectively, i.e. the higher value of β in Fig. 3(*b*) allows the use of a valve with a longer grid recovery time.

The ratio of V_d to V_0, however, shows that the penalty for this is that the output power and power factor are approximately halved for the same size of inverter tank and output transformer. Thus in practice there is a maximum allowable recovery time to produce an economic design. Assuming a commutation time of 10°, and an output power factor of 0·65, this maximum time is about 45°, i.e. 125 microsec at 1 kc/s or 62 microsec at 2 kc/s, including safety margin. This compares with grid recovery times of 500–2 000 microsec in conventional grid-controlled mercury-arc rectifiers.

In practical operation, the deionizing time allowed varies throughout the supply frequency cycle due to ripple in the direct current, and a margin must also be allowed for variations from the optimum value of β caused by the changes in the load circuit during the heating cycle, especially with manual control of the frequency.

(3.3) Commutation Factor

At the end of each m.f. conduction period the anode current is reduced to zero over the angle u, and the anode is subjected to the sudden application of reverse voltage; it is well known that the tendency of the anode to backfire is then increased by an increase in either the rate of change of current or the applied voltage. Both these factors are increased (especially the voltage) by working at a larger angle of advance β [Figs. 3(*a*) and 3(*b*)], and this represents an additional reason why it may not be possible to operate at full current with large values of β. Similarly, excessive reduction in m.f. transformer reactance to reduce the commutating time at the higher frequencies (and thus compensate for long grid recovery times) will increase the rate of change of current and hence the tendency to backfire. This is why operation is not practicable in a high-power inverter with the commutating capacitor connected directly between the two anodes, as can be done with small laboratory models.

When the grid recovery time can be kept within its economic limit, the combination of recovery time and commutation factor will determine the rating limit of the inverter valve. This

limiting output is reached for any given frequency and other operating conditions when an increase in β will result in a backfire, and a reduction in β will result in the anode refiring due to insufficient deionizing time being allowed.

The effect of the backfires discussed above is to short-circuit the m.f. transformer for part of one m.f. cycle and to prevent the deionization of the control grid, so that the anode refires when it again becomes positive. This results in a failure to continue inversion; but, as the backfiring anode is connected to a supply frequency phase which is carrying forward current, there is no backfire on the supply frequency transformer.

(3.4) Valve Construction

The inverter valve consists of a steel tank with six external anode arms and a mercury-pool cathode with conventional ignition and 3-phase excitation circuits. The modifications required to make it suitable for m.f. service are all concerned with the anode and grid structure shown diagrammatically in Fig. 9.

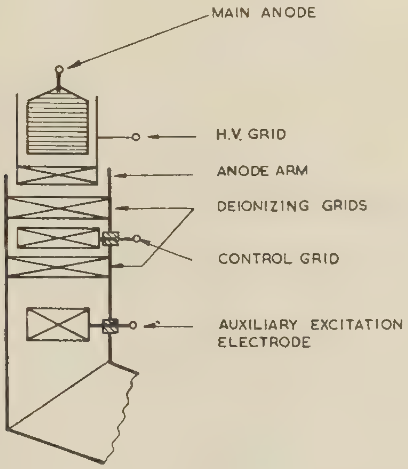


Fig. 9.—Arrangement of anode and grids in inverter valve.

The theory of operation of grids in the presence of ionization is well known,[5, 6, 7] and the principal factors in obtaining very rapid deionization are as follows:

(*a*) Low current density and mercury vapour density to allow rapid diffusion of the mercury ions to the deionizing surfaces.
(*b*) The use of deep closely-spaced grid bars and closely-spaced deionizing surfaces round the grids.
(*c*) The use of a relatively-high negative grid voltage, although it does not greatly increase the speed of removal of ions, can help the grid to regain control while there is still appreciable ionization present.

Compliance with requirement (*a*) is largely ensured by the use of a valve of comparatively low current and high voltage rating. Requirement (*b*) is catered for by placing steel deionizing grids at tank potential closely above and below the steel control grid.[8]

In order to ensure ability to withstand the high peak voltage ratings required, the anode is surrounded by an h.t. potential-dividing grid structure, which also protects the insulating surfaces from contamination by graphite particles sputtered from the anode surface by the high-voltage ion bombardment.

In spite of the high rate of deionization, it is of course essential that the inverter should conduct reliably and without delay when required whilst using the minimum grid control power, and this is ensured by the provision of an auxiliary excitation electrode mounted below the grid structure in each arm and supplied with current from the excitation system.

Owing to the ionic bombardment of the anodes at a much higher frequency and voltage than in normal rectifier service, it has not been found possible to obtain satisfactory long-term operation at maximum ratings with a sealed-off valve. A small pumping set is therefore used, consisting of a continuously-operating mercury-vapour diffusion pump followed by a reservoir tank and provided with automatic protection against supply or pump failure. The reservoir tank is evacuated occasionally by means of a rotary vacuum pump under manual control. The losses of the valve are largely removed by conventional fan cooling, but in order to obtain the best possible deionization at high ambient temperatures, a small amount of water cooling is provided by copper piping fixed externally to the inverter cathode and condensing dome. As the cathode is earthed, no insulation difficulties arise.

(3.5) Valve Operation

With the construction described above, grid recovery times of approximately 30–80 microsec are obtained, depending on current and other operating conditions. An output of 250 kW is obtainable at 1 kc/s, but the usable rating falls off with increasing frequency to about 100 kW at 2 kc/s.

One valve, which has now been in service for three years, is automatically switched on to inversion as required for the process, and has thus delivered m.f. power for 4 000 hours out of about 6 000 hours of operation. Operation in regular service is reliable, and the valve shows no signs of deterioration. Service experience with other valves gives no reason to suppose that this performance is not typical.

(4) TRANSFORMERS, REACTORS AND OUTPUT CIRCUIT

(4.1) Supply Transformer

The supply-frequency transformer follows normal rectifier-transformer practice, having a 3-phase inter-star secondary. Since the cyclo-inverter cathode is earthed, this secondary winding must be insulated for high voltages to earth at m.f. and supply frequencies.

(4.2) Cathode Reactor

The inductance chosen must maintain continuity of cathode current with about 60 to 70° of supply-frequency grid-firing delay, and should also limit the rate of rise of fault current under rectifier short-circuit conditions to two or three times full load in the first half-cycle of the supply frequency. High-speed grid blocking prevents further rise in fault current.

(4.3) M.F. Inverter Transformers

The detailed design of these single-phase transformers is a specialized subject, but some of the factors which influence the design should be mentioned.

The principal problem, which is made more difficult by the high voltage involved, is the low value of leakage reactance required between each of the primary windings and the secondary. One solution is to wind the primaries as three separate centre-tapped windings on a common single-phase core, and have six parallel secondary windings, each closely coupled to a half primary winding.

Subdivision into further parallel paths is often convenient where the output voltage required is below 1 000 volts. As each primary winding carries current for a sixth of the total time, the utilization of both primary and secondary windings is low. Skin effect limits the economical radial thickness of conductor suitable for any particular frequency.

Core loss is almost entirely caused by eddy-current heating. Reduction in lamination thickness helps to reduce this, but

because of handling and assembly difficulties, standard 0·014 in thick silicon-iron alloy has been used at relatively low flux densities.

(4.4) The Induction Furnace

(4.4.1) The Inductor.

The design of a coreless induction furnace is complex, since the impedance it presents to the inverter depends upon the permeability and resistivity of the charge at the working field strengths and temperatures, and the degree of coupling between the inductor and the charge.[9, 10] The efficiency of the inductor is obviously important in determining both the power cost per ton of metal heated and the capital cost of the m.f. supply equipment. The winding is constructed of water-cooled high-conductivity copper tube, and since the inner circumference of a spiral coil has a lower reactance and higher current than the outside, the losses may be reduced by concentrating the copper

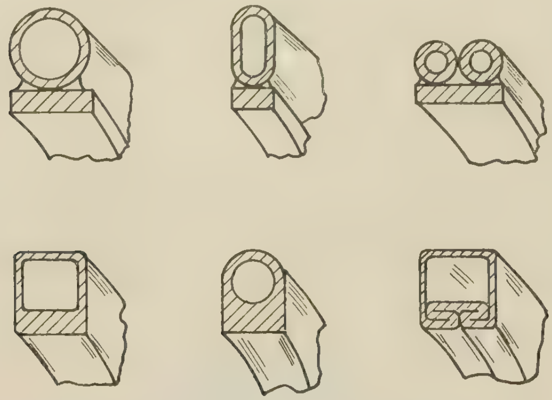


Fig. 10.—Conductor sections for furnace inductors.

section near the inside circumference. This can be done by the use of the special copper tube sections shown in Fig. 10.

Table 1 shows some examples of installations which could be supplied by an m.f. inverter of 250 kW output, and the rate of production to be expected with a furnace thermal efficiency of 70% and an inverter efficiency of 90%.

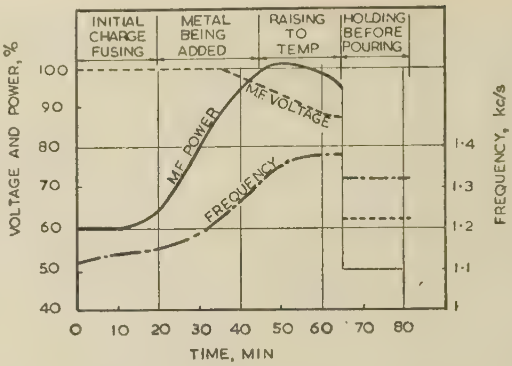


Fig. 11.—Typical melting cycle of 100 kW inverter-furnace combination.

the decrease due to the short-circuited-turn effect, which is more marked at the lower temperatures.

The progress of a melt in a melting furnace is shown in Fig. 11. Initially, the power factor is very low, being little more than the unloaded power factor of the furnace, but it increases as the pieces of the charge fuse together. More charge is then added until a full molten charge is obtained and the power factor is about 0·15 to 0·2. Full power is left on until the desired pouring temperature is reached; it may then be necessary to hold the temperature at this figure for a short while at reduced power input. The power may be reduced to about 25% by grid control of voltage, and still further by changing the input transformer primary connections from delta to star.

During the melting cycle, changes take place in the effective inductance and resistance of the furnace. The facility with which the inverter frequency may be manually or automatically adjusted to compensate for these changes makes it unnecessary to switch capacitors in the load circuit as is normally done with m.f. alternators.

An inductor for heating billets or tubes to temperatures suitable for annealing or forging usually works at a higher power factor due to the better coupling obtained between inductor and load. Power factors range from about 0·2 to 0·4.

The billets may either be continuously fed through one or more

Table 1

RATE OF PRODUCTION OF INVERTER-FED HEATING INSTALLATIONS

Duty	Material	Inverter MF output	Inverter efficiency	Furnace capacity	Heating time	Rated output	Ratio
		kW	%	cwt	min	lb/h	lb/kWh
Melting	Steel, steel alloys	250	90	6	45	900	3·2
Melting	Non-ferrous (brasses and bronzes, etc.)	250	90	6	30	1 350	4·85
Billet heating 1250° C	Steel, steel alloys	250	90	–	–	1 800	6·5

(4.4.2) Characteristics of the Charge.

The heat input to the charge is a complex function of resistivity, and load materials may be divided roughly into two groups, i.e. high resistivity where the 'hot' resistivity is of the order of 100×10^{-6} ohm-cm, and low resistivity where the 'hot' resistivity is of the order of 10×10^{-6} ohm-cm. The former group includes most ferrous metals, and the latter such non-ferrous metals as copper and aluminium.

Permeability of a magnetic charge only affects the impedance in the initial heating time before the Curie point is reached; any increase in coil inductance may in any case be counteracted by

inductors, representing an almost constant load, or individually loaded into inductors as required. In the latter case, the inverter can easily be switched off when the inductor or inductors are not loaded, leaving only small excitation losses. This can result in a considerable saving of power, since the no-load losses of heating inductors are of the same order as the full-load losses. Almost instantaneous restarting is obtained when power is required.

(4.4.3) Choice of Frequency.

The highest frequency obtainable from an inverter is not necessarily the most suitable, particularly if a wide range of work

is involved. The choice of frequency should be based on the commonest size of work, provided that it is tolerable to heat some of the smaller items with slightly lower efficiency.

With a frequency of 1·5 kc/s, the minimum size of object that can be heated economically with solenoid-type inductors varies between 2 in-diameter (or equivalent cross-section) bar for steels and alloys with similar hot resistivities, and $\frac{5}{8}$ in-diameter bar for copper, aluminium and alloys with similar low values of resistivity. For sizes of charge above this minimum, the frequency is not critical, so that an inverter with a limited frequency range is suitable for a wide variety of work. For sizes well above the minimum, and with a given inductor, charge and m.f. voltage, more power can be put into the charge at the lower than at the higher end of the frequency range. In a typical case, the speed of heating was inversely proportional to the frequency over a 1·5:1 change in frequency. Full melting furnaces usually provide a charge well above the minimum size for efficient heating.

(4.5) Capacitors

The capacitive reactive power required to bring the lagging furnace power factor to unity, plus sufficient to make the circuit as a whole present a typical leading power factor of 0·7 to the inverter, varies between 11 times and 3 times the power output with furnace lagging power factors from 0·1 to 0·4 respectively, and is calculated in the usual way.

As mentioned earlier, the ease with which the inverter frequency may be adjusted to cater for changes in load characteristics eliminates the need for on-load switching of capacitors. However, the size and cost of the capacitor bank increases in proportion to the frequency range of the equipment, since the capacitors must be rated for the full voltage at the maximum frequency.

Although some oil-filled naturally-cooled or externally-water-cooled capacitors are still used for this type of service, the tendency is to use oil or chlorinated diphenyl-filled capacitors with internal water cooling, with considerable saving in space.

(5) CONTROL CIRCUITS

Control circuits have to be provided for the following purposes:

Excitation of the inverter valve on the lines of that provided for a normal mercury-arc rectifier.
M.F. drive for the control grids of the valve.
Supply-frequency grid control of the valve as a rectifier to provide m.f. output voltage control.
Initiation of m.f. inversion.
Special protection against inverter fault conditions.

(5.1) Excitation

Normal excitation of the valve is provided from a 3-phase source, the six excitation anodes and six auxiliary excitation electrodes each being grouped into three pairs to correspond in phase with the three main anode pairs.

(5.2) M.F. Drive for Control Grids

(5.2.1) Self-Excited Circuit.

Early experiments on a full-scale inverter (200 kW) showed the inadequacy and inflexibility of the self-excited type of circuit shown in Fig. 4. This employed a phase-shift network interposed between m.f. output terminals and the control grids. An LC ringing circuit was used for providing starting impulses which were injected into the main feedback network to the control grids.

It was found that the grid impulses, particularly those produced by the starting circuit, were not sufficiently steep-fronted to prevent hesitant firing of the control grids. The decrement of the starting oscillations during the critical starting period mentioned in Section 2.3.1 also made starting difficult by providing insufficient impulse amplitude when inversion should begin; and the frequency of the starting impulses, being controlled by fixed steps of inductance and capacitance, could not be smoothly adjusted for different load conditions.

(5.2.2) Electronic Drive Circuit.

The self-excited circuit obviously gives a direct control of the firing angle β. The use of a separate grid drive without feedback also gives satisfactory control due to the effect of the inverter current on the output circuit mentioned in Section 2.3.2. Thus, for example, an increase in drive frequency will cause the grid firing point to advance on the anode wave and increase β to a new stable value at which the output circuit (and anode voltage) is oscillating at the new drive frequency.

The circuit now used is shown in Fig. 12, and consists of a

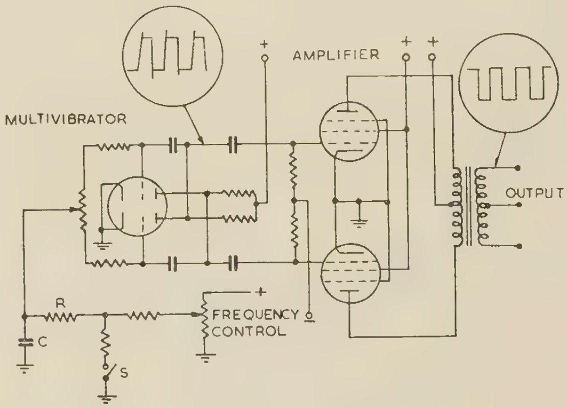


Fig. 12.—Electronic grid impulsing circuit.

balanced multivibrator and amplifier producing steep-fronted square waves. The frequency is linearly dependent upon the multivibrator grid bias, which can be controlled manually or automatically, and the amplifier gives an output of 40–50 watts.

As mentioned earlier, it is advisable to start the inverter action with an increased angle β, i.e. grid impulses which are momentarily of a higher repetitive frequency than subsequently. This is accomplished by a contact S on the starting relay, which closes to reduce the multivibrator bias to the operating level through a time-delay circuit RC. The transient change in frequency required is not critical, being between 10 and 20%.

(5.2.3) Automatic Frequency Compensation.

As mentioned earlier, too small a firing angle gives too short a deionizing time, and too large an angle produces excessive peak inverse voltage and low power factor.

Fig. 13 shows the limits of reliable operation for an inverter with two typical furnace LC combinations loaded with varying amounts of metal to be heated.

Owing to the reduction in inductance as the charge is increased in the furnace, the minimum frequency, limited by deionization considerations, is raised slightly, causing the curves (a) and (a') to lean over to the right at the higher loads; the disadvantages of running at one fixed frequency are shown by the limited load range obtainable along, for instance, the line OP.

A circuit has therefore been devised to maintain a constant leading power factor at the output of the inverter, and thus to maintain the angle of advance β, and the deionizing time, approximately constant.

This circuit consists of a phase discriminator network, coupled with a backing-off circuit, and is shown in Fig. 14.

The voltage across the points A and B is proportional to current; it is a maximum when the current and voltage input

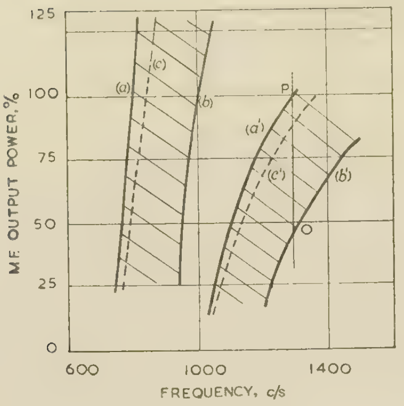


Fig. 13.—Limits of inverter operation.

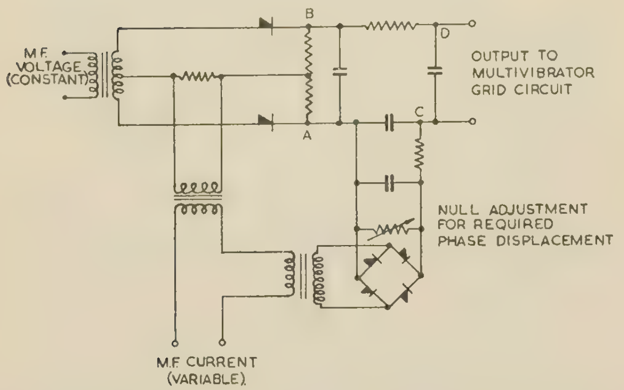


Fig. 14.—Phase discriminator for frequency control.

signals are in phase and a minimum when they are in quadrature. The back-off voltage at CA is pre-set and enables the voltage at CD to be adjusted to zero for the desired phase relationship between m.f. voltage and current, independent of current amplitude. Any deviation from the desired value produces a d.c. signal at CD which corrects the frequency and brings the phase angle back to the required value.

The inverter can then maintain optimum stable operation over wide changes in load. Curves (*c*) and (*c'*) in Fig. 13 show the operation using this circuit.

(5.3) Output Voltage Control

(5.3.1) Basic Circuit.

As mentioned in Section 2.2, voltage control is obtained by modulating the m.f. impulses to the control grids of the inverter valve at supply frequency.[11] The basic circuit for one pair of control grids only is shown in Fig. 15.

When the thyratron is not firing, the m.f. grid pulses are bypassed to the negative-bias supply through the clamp rectifiers and the relatively low resistance of the thyratron load, and the inverter anodes are prevented from firing.

The thyratron anode voltage supply consists of a combination of two sine waves, covering the full working range of conduction angle of the inverter valve anodes; when the thyratron fires, its cathode potential becomes positive to the inverter cathode, and the inverter grid pulses can also become sufficiently positive to fire the control grids. Control of the thyratron firing angle is by means of a fixed a.c. and variable d.c. bias. Variations in this bias level can thus control the point in the cycle at which each pair of inverter anodes starts conduction.

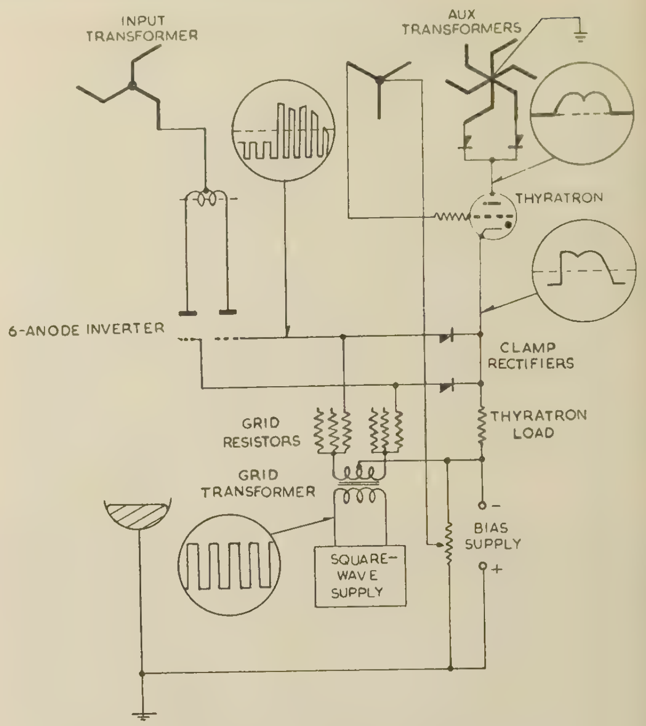


Fig. 15.—Grid-modulation circuit.
One phase only is shown for clarity.

(5.3.2) Automatic Control.

Automatic control of output voltage is achieved by feeding into the thyratron bias circuit a direct error voltage proportional to the difference between the actual and the desired value of m.f. output voltage, and obtained from a neon stabilizer bridge circuit. Resistance control of the rectified m.f. voltage applied to the bridge provides a manual adjustment for the automatically controlled m.f. output voltage.

Stabilization of the combined automatic frequency and voltage controls is achieved by increasing the time-constant of the output signal of the former, and providing phase advance in the latter circuit by means of an anti-hunting transformer.

(5.3.3) Starting Circuits.

When ready to invert, a relay momentarily reduces the bias on the thyratrons from cut-off to a point where they fire approximately 60° retarded for two or three supply-frequency periods. This applies two or three bursts of m.f. impulses to the inverter control grids with the equivalent of 50% grid control of voltage.

Failure to invert on the first operation of the relay causes it to drop out for an instant and operate again, and thus to continue cycling at about two operations per second until inversion is successful or adjustments are made.

When inversion starts, the relay is held in by a feedback circuit, and a second, slower relay changes over the bias of the thyratrons from the 50% starting-up setting to the value at which the manual or automatic controls are set.

(5.4) Protection Circuits

Normal circuit-breakers and h.b.c. fuses are used in the 50 c/s power supply to the inverter. This then leaves the following protection requirements which are particular to this type of equipment.

(5.4.1) High-Speed Protection.

In the event of the inverter action failing for any reason, the inverter valve acts as a 3-phase rectifier on short-circuit with the

main reactor only limiting the rate of rise of short-circuit current. It is therefore essential to block the valve grids as quickly as possible under fault conditions, so that damage may be prevented.

This is done by a high-speed polarized relay which applies a large blocking bias to the output valves of the m.f. grid impulse amplifier. This removes all m.f. grid impulses in approximately 1 millisec, leaving the control grids of the inverter valve connected only to the maximum negative-bias voltage.

Inversion failure is detected by a differential arrangement of the relay coils which is sensitive to any sudden fall in the m.f. output voltage, and has a time-constant sufficient to hold the relay closed until the fault current has died away.

A back-up direct over-current operation is obtained by having another coil of the relay connected to a shunt in the main cathode circuit. This may be set to approximately twice full load and will therefore operate on overload or short-circuit conditions.

The speed and safety of operation is such that the blocking is applied well within the first half-cycle of supply frequency during which a fault has occurred, and operation of the feeder circuit-breakers or fuses does not occur. After clearance of the fault, the inverter automatically restarts.

(5.4.2) **Over-Voltage Protection.**

The occurrence of output voltages exceeding 120% of normal (e.g. due to incorrect operation of the manual controls) is detected by a relay which stops further inversion until the equipment is manually restarted.

Instantaneous over-voltage protection, set at a higher value, is provided by spark-gaps across the high-voltage primary windings of the m.f. transformer.

(5.4.3) **Furnace Earth Leakage.**

This problem is common to all m.f. induction furnaces whatever the source of m.f. power. One important feature of the m.f. inverter, however, is that, should molten metal or other charge materials cause short-circuited turns in the furnace coil, the inverter action will stop instantly before extensive damage due to arcing, etc., can occur. In this respect, therefore, the inverter is inherently self-protecting.

Provision is generally made in melting furnace installations for protection against shocks received due to hot metal coming into contact with the furnace winding while the operator is in contact with the molten charge when stirring or adding material. One of several possible earth-leakage systems is usually employed.[13]

Such protection may be used either to stop the inverter action in the same way as the over-voltage device, or to trip the main-supply circuit-breaker.

In installations for heating work up to forging temperatures, it is advisable to use earthed mechanical handling gear if the work is to be moved with m.f. power on. Many refractory linings are conductive and may give rise to shocks if a charge is dragged along the lining when held by the operator.

(5.5) Arrangement of Control Circuits

A single cubicle of medium size is used to house all the control and excitation circuits, and this may be placed in any convenient position relative to the furnace or the inverter enclosure.

'On' and 'off' pushbuttons are provided for the main circuit-breaker, and for starting and stopping the m.f. inverter.

Instruments are provided for indicating m.f. output power, current, voltage and frequency, as well as for the inverter valve excitation and cathode currents. To make maintenance easy, a checking meter is provided with a flexible lead and jack-plug. All the key circuits are fitted with jack sockets so that a fault in a particular circuit may be quickly located. Individual circuit sections, e.g. frequency control, voltage control, are mounted on subdivided panels, and the wiring is arranged so that any section may be removed easily for detailed examination.

Pre-set adjustments used for initial setting-up are behind doors, as also are the checking and other non-operational instruments and controls. This leaves on the outside the minimum controls necessary for normal operation.

The electronic valves used have proved extremely reliable; gas-filled types have sometimes had to be replaced after about 2000 hours' service, but the hard valves in general seem to have lives in excess of the 6000 hours' service so far achieved.

(6) TYPICAL INSTALLATIONS

(6.1) Melting

Fig. 16 shows a block plan of a cyclo-inverter rated at 100kW, 1kV and 1·5kc/s, feeding a 200lb furnace for melting high-temperature aircraft alloys, the incoming supply being 420 volts, 3-phase and 50c/s. The main inverter components, including the valve, transformers, incoming supply contactors and some capacitors, are housed in a ventilated sheet-steel enclosure. The 50c/s and m.f. transformers and the d.c. reactors are mounted in a common tank. Access to the enclosure is via double doors interlocked by a key system to the incoming supply isolator. A door-operated switch earths the three high-voltage secondary connections of the supply-frequency transformer when the doors are opened.

The control cubicle is placed near the furnace, which is about 20ft from the inverter enclosure. The cubicle contains all the excitation and grid-control equipment, indicating instruments and manual controls, as described in Section 5.6. Main-supply

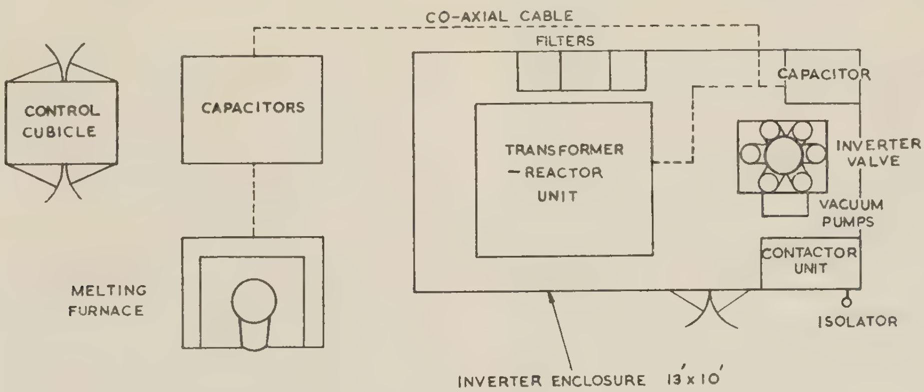


Fig. 16.—100kW 1·5kc/s inverter-fed melting plant.

contactor closing and tripping and m.f. starting and stopping are under pushbutton control. A change-over switch interlocked with the supply tripping is provided for star/delta selection for wide-range power variations.

The furnace is mounted in a motor-operated tilting frame, the m.f. power connections being made through knife-type contacts when the furnace is lowered for melting. A limit switch prevents operation of the inverter when the furnace load is not connected to its terminals.

Should molten metal break through the walls of the lining and come into contact with the furnace coil, the inverter is stopped by an earth-leakage relay connected to an electrode in the base of the partly conductive furnace lining. A checking circuit is provided.

Sufficient capacitors to tune the furnace load to approximately unity power factor are mounted immediately behind the furnace, and the combination is fed by m.f. coaxial cable from the inverter enclosure.

Access to the inverter enclosure is only required for routine maintenance, the inverter being under the complete control of the foundryman at the furnace location. Because of this and the fact that a melt takes about 60 min, manual control of frequency with some automatic voltage control is used.

The frequency and voltage may then be adjusted from time to time to suit the condition of the melt, and the operator has ample time to do so.

The average furnace power input is about 75 kW with peaks of 100 kW as shown in Fig. 11. The inverter full-load efficiency is 82%.

The input power factor is unity on maximum voltage at full load, corrected from 0·95 displacement factor by the harmonic filter capacitor. Proportionate reduction in displacement factor occurs with grid control of voltage, but, owing to the fixed capacitor and reduced loading, the overall power factor remains high.

(6.2) Billet Heating

In a typical installation a cyclo-inverter rated at 200 kW 250–300 volts, at 1–1·5 kc/s, supplies power to one or more heating stations in a forging shop. The main inverter components are again housed in a ventilated steel enclosure, and the control cubicle is built into this structure. The 50 c/s and m.f. transformers are mounted in a common tank. Capacitors are connected at each furnace to bring its overall power factor approximately to unity, in order to minimize the duty on the coaxial cable which carries m.f. power from the inverter to the coils.

The enclosure access door is fitted with mechanical and electrical interlocks and an automatic earthing device for the high-voltage circuits. This application calls for operation of up to three stations without mutual interference, and the loading at each station varies with different sizes of coil and work from between 40 and 80 kW fully loaded to 18 and 35 kW empty. The total load is a combination of this, isolators inside the enclosure enabling the required heating stations to be connected to the inverter.

Automatic voltage control and automatic frequency compensation are provided, so that little manual adjustment is required.

An earthed rolling carriage with air-operated clamps is used to carry the work-pieces at each furnace, and a great saving in power is effected by arranging for trip switches on these carriages to start the inverter only when power is required at any of the furnaces and to stop it when all are empty. The load cycle consists of about one minute heating time, plus a few seconds for changing the billet.

Adjustment of the controls is required only when the furnace arrangements are changed. The furnace operators have access to m.f. 'on' and 'off' and circuit-breaker 'trip' controls only.

The inverter efficiency is shown in Fig. 17, and the overall thermal efficiency from the inverter input is about 60% on fully-

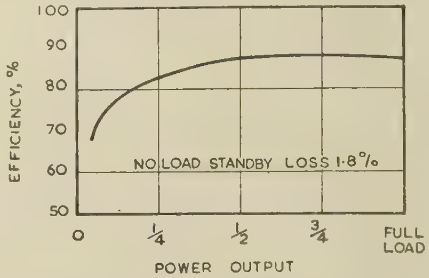


Fig. 17.—Inversion efficiency of 200 kW installation.

loaded inductors. In practice, however, the loading is variable and intermittent, with inversion automatically stopped for about one-third of the time.

(7) CONCLUSIONS

As a result of the developments described, it is considered that the mercury-arc m.f. inverter presents a technically and operationally satisfactory alternative to motor-alternator sets in suitable applications. The inverter has advantages of ease and flexibility of control, higher efficiency and static operation to set against its relative unfamiliarity and greater circuit complication.

(8) ACKNOWLEDGMENTS

The authors would like to express their thanks to the English Electric Company Limited for permission to publish the paper, to Mr. J. E. Boul for his interest and encouragement, and to their colleagues with whom the work has been carried out.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 13TH MARCH, AND BEFORE THE NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 18TH MARCH, 1958

Dr. R. H. Barfield: The problem of frequency conversion has been of great importance ever since the invention of wireless telegraphy some 60 years ago, and the authors are associated with a long line of illustrious inventors, such as Marconi, Franklin, Poulsen, Alexandersen and Goldschmitt. Industrial high-frequency heating, however, has been more or less content so far to take over from this field of radio what are really only slight modifications of the method of frequency conversion which are available to meet the demands of the older art. It is therefore not unnatural to ask why, at this comparatively late stage, it appears to be thought desirable to devise other methods. Perhaps as an induction-heating engineer I can answer this question. The reasons are, I think, that induction heating has itself developed new demands for higher powers and also lower frequencies than radiocommunication generators. These higher powers represent running costs of a high order and therefore demand a higher efficiency than is necessary in radio transmitters. Another difference is that induction heating is inevitably associated with a load whose reactance and resistance both change drastically during the heating process.

When this project was first started, several years ago, the authors hoped to produce a high-frequency generator having rather more advantages over the motor-alternator than the apparatus which forms the subject of the paper. It was hoped that an inverter could be produced based on one or more standard grid-control steel-tank rectifiers which would be capable of delivering very large powers at frequencies up to 2 kc/s and having the characteristics of self-tuning, simplicity of operation and a price considerably lower than that of the equivalent motor-generator. It is clear that the task proved rather more difficult than expected, and unfortunately during this development some of these ideals have had to be sacrificed. Indeed, from the description of the complicated nature of the transient phenomena associated with the mercury-arc inversion, one is not surprised that this should be the case. Nevertheless, do the authors still consider that there is a possibility of attaining the ideals with which they originally set out, for I think this would be well worth while?

Perhaps it might be well to ask ourselves what sort of generator or frequency convertor would fulfil all the possible requirements for industrial induction heating. What one would really like to see would be a unit somewhat resembling a transformer, occupying space of the same order for the same power rating. This unit would be contained in a box or sealed case, having nothing on its outside except the input and output terminals and possibly a manually operated voltage adjustment. This latter feature is, indeed, very important in induction heating, because one of the major difficulties facing the induction engineer is to design a heating inductor which will work on the right voltage when he has finished it. The frequency of this ideal frequency convertor would automatically adjust itself to give unity power factor under the varying load. Its conversion efficiency would be high —at least 95%—and its life and maintenance cost would also be comparable to those of a first-class transformer. If the authors, by their further efforts, can bring the work to this stage, they will indeed be fulfilling a great service to induction heating.

Dr. W. G. Thompson: The various static methods available for producing high frequency would appear to be constrained by the need to have the operating conditions in the inverter fixed by the parameters of the valve devices used for generating the high frequency. The difference between the present and the early methods is that the former does this conversion by means of mercury vapour. Possibly it would be simpler to use a high-voltage mercury-arc rectifier as such and do the high-frequency generation in two separate single-anode vessels. The authors have had to fit a pump to the rectifier. It is a well-known degassing technique to bombard the anode of a valve or a vessel at high frequency. I do not know whether the authors hold out any possibilities in the future for dispensing with the pumps.

The authors refer to the use of deep steel grids in their rectifier instead of graphite grids. Steel grids were used in rectifiers many years ago and apparently the present application warrants a reversion to earlier practice.

When a rectifier is provided with heavy deionizing it becomes rather temperature-sensitive, but the authors have made no reference to starting under cold weather conditions.

The control-circuit complication is no great disadvantage, because the fact that it is static permits a degree of complication. If this static apparatus is reasonably quiet, it might be an additional gain over high-frequency machines.

The authors mention that the apparatus has proved reliable, running for several thousand hours. Do they think that in future, when the application and working of this system has been reconsidered with the possibility of cheapening manufacture, it will be a truly commercial and competitive device?

Mr. J. Terry: One of the two equipments referred to by the authors and with which I have been associated was installed in 1951. Amongst the modifications was the replacement of the pumpless valve by one fitted with a pumping set. The pumped valve has been in operation since 1954 on a 2-shift basis, so that it must have delivered power at medium frequency for some 8 000 hours. During the past eight months repairs and adjustments have involved an expenditure in time of 105 man-hours, the only renewals being two small valves.

The inverter is extremely sensitive to temperature and starting-up troubles are common, particularly in cold weather after the weekend shut-down. There have also been troubles from flash-over on the transformer h.v. insulators, owing to dust in the shop. These conditions indicate the desirability of housing the equipment in a special enclosure with air-conditioning.

Although at the time the equipment was installed the absence of noise and foundations were claimed as advantages, I believe that recent and current developments in rotating machines are narrowing, if not eliminating, the margin in favour of the inverter.

I am not happy about the method of dealing with earth leakage. It is not always possible to obtain a low-resistance earth for the mechanical-handling gear, and oxidation both of the charge and the handling gear may give a bad contact. A suggested method is to bring out the centre tapping of the secondary of the medium-frequency transformer, earthing it through a suitable leakage relay.

What are the possibilities at lower frequencies, say 250–1 000 c/s? I believe there to be a requirement in this frequency range for units of, say, 0·5–1·0 MW; in the forging industry, 200 kW represents about half a ton of steel per hour when heated at 1 200° C.

Mr. D. I. Spash: The authors say that the inverter is capable of generating frequencies between 1 and 2 kc/s. They also state that a typical inverter has a peak efficiency in the region of 1 kc/s and that, if operated at 2 kc/s, the power output is approximately halved. From this one can only reach the conclusion that the inverter used on an application necessitating a frequency of 2 kc/s (and higher, if possible, for the future) must be a rather inefficient conversion unit when compared with the motor-generator.

Induction heating of billets sometimes involves the use of low-frequency plant (50–60 c/s) for pre-heating, followed by a motor-generator set operating at 2–3 kc/s for the final heating to forging temperature. This is a typical combination of two types of equipment for the efficient heating of billets about 3 in in diameter.

The frequency used in the motor-generator set is usually about 2–3 kc/s for small 1 in diameter billets and lower for larger billets. In heating small-diameter billets the higher frequency is essential if reasonable overall efficiency is to be achieved. Perhaps the authors would comment on these approximate figures and, in particular, on whether the inverter has not a rather restricted use in billet heating, compared with motor-generator equipment, since the maximum power of a single inverter unit is only 200 kW and much higher powers are necessary for heating larger billets at the lower frequencies.

The other application mentioned is melting. I believe that it is generally accepted that a considerable stirring action occurs if too low a frequency is employed. This is extremely detrimental to the life of the crucible as well as from the metallurgical aspect. I am therefore surprised that an inverter operating at 1–2 kc/s has been employed for melts as small as 200 lb or less. Have any adverse stirring effects been experienced? Do the authors not consider the inverters more suitable for 10 cwt melts? What do the authors consider the future possibility with regard to maximum power rating of inverters? What is the maximum power output they envisage from any single steel-tank inverter, whether of the mercury-pool-cathode type, with conventional ignition, or other design? Also, have they considered a completely glass-bulb type?

Mr. K. F. Raby: It is inevitable that comparisons should be made between the mercury-arc inverter and the motor-alternator which is the established source of medium-frequency power, and it is important that these comparisons should be made with the best and most recent practice in motor-alternator design.

Fig. A compares the efficiency of the mercury-arc inverter (as quoted in Fig. 17 of the paper) with that of a typical 200 kW 1 kc/s motor-alternator. At one-quarter load the efficiencies are comparable, while at higher loads the advantage is slightly with the motor-alternator. The standby losses of the inverter are admittedly lower, but it is unlikely that they will have a very significant effect on overall operating costs in a typical duty cycle.

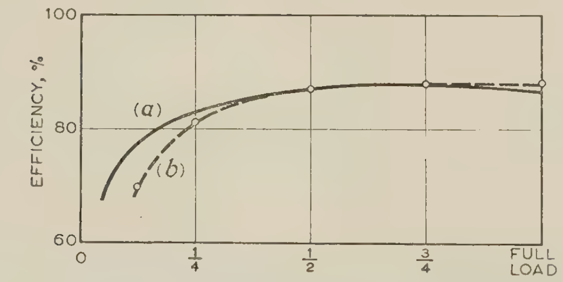

Fig. A.—Comparative efficiencies of 200 kW 1 kc/s motor-alternator and mercury-arc inverter.

—— Inverter (from Fig. 17).
---- Alternator.

No-load standby losses	
Motor and excited alternator	5·2%
Motor and unexcited alternator	3·2%
Inverter	1·8%

The choice between conventional rotating machines and a static equipment involving electronic and high-vacuum techniques must rest with the customer. The modern trend in motor-alternator design is towards a compact set with integral water-cooling, mounted on resilient supports and requiring no special foundations. The set is often built with a vertical shaft to occupy the minimum floor space. Low residual voltage and a short field time-constant enable capacitor switching to be carried out at much reduced voltage.

It is indeed unfortunate that the mercury-arc inverter is inherently limited to frequencies of 1–2 kc/s. The medium-frequency range used in induction heating extends to 10 kc/s, which represents the practical limit for rotating machines. At 10 kc/s the motor-alternator set becomes larger and much less efficient, and consequently there is great scope for any economic alternative which can be devised.

Mr. J. Glen: I have recently been engaged on the development of a m.f. convertor using glass-bulb mercury-arc rectifiers, and while I agree that the equipment described presents a technically and operationally satisfactory alternative to the alternator, I wonder whether the steel tank rectifier is competitive.

Concerning the rectifier itself I should like to ask the authors the following questions:

(*a*) Could the present rating of 250 kW at 1 kc/s be extended, either by further modification or a new design?
(*b*) Was the use of a sealed tank precluded by initial degassing difficulties?
(*c*) What is the minimum working ambient temperature?

The controls have been concentrated at the rectifier itself, probably at the cost of simplicity and economy. The starting method is very ingenious, but it relies on complex electronic gear and may require occasional manual adjustments. Can the latter be made by unskilled operators? As an alternative, a contactor in a part of the capacitor bank offers a simple and extremely reliable starting.

The m.f. power control using an additional grid is attractive at first sight, but introduces further complications at the rectifier and in the circuit. Again, a standard 3-phase 50 c/s regulator would give 50% m.f. power control with ±15% voltage adjustment, and a star/delta switch would provide further reduction.

Is the use of the desirable self-excited circuit impracticable because of the complexities mentioned above?

Mr. P. L. Lowrie: Some of the features which are given for the inverter are also obtainable with motor-alternators, e.g. the generator output voltage is varied by field control for heating power control and empty-heating-coil losses are saved by opening the field contactor. The frequency variation obtainable with an inverter is no doubt an advantage when dealing with induction melting and with single-coil induction billet heating. However, there is an increasing number of billet heating applications which involve a number of heating equipments operating in parallel from a high-frequency source. It is then essential to operate at a fixed frequency and a fixed voltage in order to prevent interference between different stations.

Maintenance and shut-down time are major issues with any user of frequency-converting equipment, and I should like to stress that a steel mill with a lot of associated equipment could be lying idle because one valve or one capacitor was defective in part of the induction-furnace frequency convertor.

The steel-tank rectifier manufacturers are to be congratulated for putting equipments into service on a new rectifier application before the glass-bulb rectifier manufacturers, who have been established for many more years.

A lot of work has gone into the development of steel-tank rectifiers without pumping and water cooling, and I was surprised to hear that we are again faced with them. Let us hope that further development of this inverter will eliminate both of these requirements.

In induction billet heating there are difficulties with temperature control by radiation pyrometers, and time control is frequently used on the assumption that a billet of a given size

heated for a fixed time reaches a fixed temperature. How would mains-voltage variation and automatic restarting after a backfire affect this?

Mr. M. G. Gibbs: From my own experience with the inverters described in the paper I believe that it would be more realistic to give the upper limit at which satisfactory inversion takes place as 1 400/1 500 c/s, above which, uncertain operation and difficult starting occur. It appears that the relatively low frequency at which the inverter is capable of working is due to the long ion-recombination time. Has any work been done on what might be called 'forced recombination'? The Vrieland generator used a 2-anode glass-bulb rectifier in which the arc was switched between the two anodes by an alternating magnetic field produced by coils coupled to the output circuit. By adopting a similar principle it might be possible to increase the number of collisions between positive and negative ions occurring in a given time, thereby decreasing the deionization time and raising the effective working frequency of the inverter.

Finally, it should be remembered that the initial work on the generator described in the paper was done a number of years ago, when rotating high-frequency alternators were difficult to obtain here. The most recent development in the rotating-machine field is the vertical-spindle alternator, and once again, in spite of the demand, it is proving extremely difficult to obtain equipment of this type which has been manufactured in this country.

Dr. R. Feinberg (*at Manchester*): In view of the practical difficulty which had to be overcome in order to achieve a satisfactory solution for starting the inverter action without modifying the output circuit, it is justifiable to ask whether it is possible to use commutating capacitors connected directly between the respective anodes and having such a capacitance that they assist effectively in the commutation process during the starting-up period of the inverter without causing at full inverter loading an excessive rate of change of current, with the consequent tendency to initiate backfiring of the valve. Each commutation capacitor might perhaps be connected in series with an adequate resistance.

It is interesting to note that an auxiliary excitation electrode is inserted in each arm of the valve. However, no indication has been given of how the auxiliary excitation electrode system is functioning, i.e. how it is connected and operated in relation to the main excitation system.

The term 'deionizing time' as used in the paper may give rise to some misunderstanding. 'Deionization time' is a recognized term referring to the performance of a gasfilled or a mercury-vapour valve, whereas 'deionizing time' in the paper describes a quantity arising from the functioning of the inverter circuit. A more appropriate term might be the expression 'forward-anode-voltage recovery time'. On the question of terminology it would further be helpful to consider that a valve used in an inverter circuit may just as well be employed in a rectifier circuit, and instead of saying 'inverter valve' a more general term should be applied, for example, 'convertor valve'.

Mr. P. W. Palmer (*at Manchester*): Several factors which are of comparatively minor importance at power frequencies become important at medium frequencies, particularly where—as here—the rectifier operates close to its limits, and it is interesting to note the authors' use of a much stiffer grid-blocking action than is usual and additional electronic control equipment to ensure reliable performance in the face of a decreasing commutating voltage and reduced deionization time.

The choice of inversion voltage and current was limited by the behaviour of a rectifier (previously developed for transmitter h.t. supplies) at these higher frequencies. It is conceivable that a rectifier designed for this service might have avoided some of the additional complications: for example, the use of alternative materials might have allowed continued operation as a pumpless unit.

I appreciate the difficulties which must have faced the authors and realize that it would be premature to condemn the system on the basis of a few experimental installations. However, since high-frequency machines are satisfactory, it would be interesting to have some comparison of the economic advantages of these systems and to know whether the noise level of this system is lower than that of a machine.

It would seem that there are several problems requiring further study, e.g. that of severe anode bombardment.

I assume that there were the inevitable preliminary troubles of a new equipment, and it would be interesting to know how the faults were distributed, both in time and between the various parts of the equipment. I imagine that the electronic equipment would have proved reliable with little replacement of components, except, possibly, for the thyratrons.

Mr. P. B. Allison (*at Manchester*): The paper is of great interest in describing an alternative to the motor-generator set for certain induction heating applications, but I feel a more detailed comparison between the two types of equipment would be of value.

As regards capital cost, could the authors indicate whether the inverter compares favourably with the motor-generator, rating for rating?

From Fig. 17 the full-load efficiency of a 200 kW inverter installation appears to be 86–87%. A comparative figure for a typical modern motor-generator set of similar rating in the 1–1·5 kc/s range would be 85%. If the capacitor bank losses in the two installations are also taken into account, it would appear that there is little difference between the two types of equipment on grounds of efficiency.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. D. L. Smart and **J. J. L. Weaver** (*in reply*): The relative costs of inverters and machines will vary in different applications. We believe that the cost of individually produced inverters of the type described and working at 1–1·25 kc/s is comparable with that of individually produced motor-generator sets, but severe reduction in inverter ratings makes them uneconomic at frequencies approaching 2 kc/s.

We do not think that the upper frequency limit for high-power inverters is likely to be greatly altered (e.g. to 5–10 kc/s) by normal development of mercury-pool valves; some radical new techniques would be required for this. Where higher powers are required, it would be better to develop circuits using two or more valves than to develop larger valves. This would give increased flexibility in application and would allow greater phase multiplication on the supply transformer.

The increasing use of power-frequency inverters and the comparatively high ratings obtained from single 6-anode sealed tanks show that there may well be good prospects of producing economic inverters in the 250–500 c/s 500–1 000 kW class if the demand is sufficient to justify the development work involved.

We think that the main cause of gassing in the existing valve may be the exposure of new graphite surfaces by the gradual microscopic erosion of the anode faces by the high-voltage and high-frequency ionic bombardment. It thus seems unlikely that a different degassing procedure or the use of different available types or qualities of anode material would enable this design

and rating of valve to be used without pumps. Steel is used for the grids instead of graphite, since it allows easier manufacture, and fault currents are too small to cause melting. Starting of the inverters was found to be difficult in cold weather, and heaters may therefore be provided under the valve to bring it to 15–20° C before starting.

Although the electronic grid control may appear complicated, it has nevertheless proved very reliable in service. Apart from starting requirements, it has the advantage of giving grid impulses of constant size and waveshape, while using smaller components than those required to make a self-excited circuit work over a wide voltage range. The additional components required for grid control of voltage are much cheaper than a mains power regulator, and involve no changes to the inverter valve. The circuit maintains the output voltage independent of supply variations, and fixed-time billet heating should be possible; if inversion failures occur, they do not normally last longer than 1 sec. In the furnace application described in the paper there does not appear to be any adverse effect due to stirring action at the frequency used.

Connection of a proportion of the capacitors from anode to anode with resistive damping would probably improve the starting conditions without making the rating worse, but would involve excessive losses. We agree that the term 'deionizing time' can be confusing, and it is not a fully defined term even in its application to valves. We have therefore modified our wording to use 'deionizing time allowed' for the period when the circuit holds the anode negative with respect to the cathode, and 'grid recovery time' for the time required by the grid to regain control.

Maximum safety is obviously given by automatic handling gear, but indirect manual handling via earthed handling gear with insulated handles has been used. High-resistance joints in the circuit between the charge, handling gear and earth would in any case vitiate the safety expected from the use of an earth-leakage relay.

DISCUSSION ON 'BRUSHLESS VARIABLE-SPEED INDUCTION MOTORS'*

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 21ST OCTOBER, 1957

Mr. J. E. Macfarlane: A.C. commutator motors comprise the most expensive parts of an induction motor and a d.c. motor. The d.c. shunt-motor characteristic exhibited by this motor is of value in practice, and even though the efficiency may be on the low side, applications can be found in which efficiency is of secondary importance. The paper shows that there is still room for research on dynamo-electric machines and that development is not confined to 'light current' subjects.

The new arrangements of induction motors as subjects for research in recent years at the Universities of Manchester, Bristol and Sheffield should encourage more students to take an interest in electrical machines instead of being attracted to electronics laboratories.

Mr. F. T. Bartho: The motor has a constant-horse-power characteristic, but so far as can be seen at present, the design does not favour 2-pole ratings. However, reference has been made in the discussion to the possibility of using a brushless variable-speed motor for power-station auxiliary drives.

This statement is conflicting, since many such drives require 2-pole motors where the torque characteristic of the drive follows a square law and the horse-power falls as the cube of the speed. Can the authors give some indication of the efficiency and power factor when the motor is running under such conditions at, say, one-third speed?

Furthermore, what is the starting torque and starting current with direct-on-line starting? Can the motor be switched on at any stated speed, and if so, what effect has this on the starting performance?

Further to the London discussion, although the manufacturing cost of the motor will have an important influence on its future commercial development, I think it is unfair to compare the cost with that of existing machines when the cost of the brushless motor has apparently not been investigated. In any case to compare this constant horse-power motor with a commutator motor having a constant torque characteristic is most misleading.

Do the authors consider that the motor has a future for those reeling drives where accurate control is not required?

Prof. F. C. Williams and **Messrs. E. R. Laithwaite** and **L. S. Piggott** (*in reply*): We agree entirely with everything Mr. Macfarlane says.

We cannot entirely understand Mr. Bartho's first comment since a 2-pole induction motor runs at nearly 3 000 r.p.m. and i normally a fixed-speed machine. Spherical motors obtain speed variation by changing the number of poles, but are essentially limited to large pole numbers. If they are ever to be used a high-speed drives, they must therefore incorporate mechanical gearing.

One would not normally employ a motor with a constant horse power characteristic for a cube-law load. We have no figure for one-third speed under these conditions, but for one-half speed both the power factor and efficiency would probably be halved

The starting torque and starting current with direct-on star are controllable by the designer in the same way as they are fo a conventional squirrel-cage induction motor. The motor ca be switched on at any speed setting. The locked rotor curren is practically independent of speed setting and may be limited b any of the conventional design techniques.

We have not so far considered the application for reelin drives.

* Williams, F. C., Laithwaite, E. R., and Piggott, L. S.: Paper No. 2097 U, June, 1956 (see 104 A, p. 102).

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Paper No. 2594 S
Apr. 1958

OPERATIONAL EXPERIENCE AT CALDER HALL

By K. L. STRETCH, M.A., Associate Member.

(*The paper was first received* 7*th October*, 1957, *and in revised form* 13*th January*, 1958. *It was published in April*, 1958, *and was read before a meeting of the* SUPPLY SECTION 16*th April*, 1958, *held in conjunction with the* BRITISH NUCLEAR ENERGY CONFERENCE, *and before the* SOUTH-WEST SCOTLAND SUB-CENTRE 22*nd April*, 1958.)

SUMMARY

The paper describes the programme carried out to commission and operate the Calder Hall nuclear power station from the time when reactor No. 1 was taken over by the operations branch in May, 1956, until the complete unit was on line at full power. Detail of the methods of carrying out particular aspects of the experimental work is left for other authors; the emphasis in this paper is on the relevance of the tests and their results to the successful operation of the Calder Hall project in particular and the prospects for nuclear generation of power in general. It also indicates the type of work and problem which operation of nuclear power stations will entail.

(1) OBJECTS

Although Calder Hall was designed primarily as a plutonium producing unit, its main interest to engineers, and electrical engineers in particular, is as the first industrial-scale application of nuclear power to the generation of electricity. Its essential purpose must not be forgotten, however, since the optimization for plutonium production markedly influenced the design in some features to the prejudice of its efficiency as a generator of electricity. So far as the generating aspect of the station is concerned, its objects can be broadly classified under four headings:

(*a*) To confirm the technical feasibility of this type of reactor. The original design studies had been based on far from complete basic knowledge; and the first and most important problem was to confirm that a power-producing reactor of this type and size could be designed and would operate efficiently with the materials selected, i.e. with carbon dioxide as the gas coolant, graphite as the moderator and natural uranium (canned in magnesium alloy) as the fuel.

(*b*) To indicate the economic feasibility of the project. Clearly in this connection the marked differences between a plant optimized for plutonium and one primarily designed as a power producer have serious distorting effects on the economics of operating the station as a power producer; but it was hoped that some information could be obtained from Calder Hall which, with suitable correction, would give an indication of the future trends of power producers.

(*c*) To confirm the safety characteristics of this particular type of reactor. One of the great attractions of the gas-cooled reactor was its considerable inherent stability and safety, which, if confirmed, made it a particularly attractive model for industrial development.

(*d*) To establish the problems and limitations involved in operating nuclear reactors of this type. An indication was wanted of whether the operation of the station as a generator was sufficiently stable and flexible for it to make a major contribution to the electricity generating programme. Experience was needed of the performance and life on load of the fuel elements, moderator and structural materials of the reactor circuit. In addition, some knowledge of the accessibility of the plant for maintenance and inspection purposes was essential.

The paper gives a historical account of the work carried out by the Calder Hall operations staff from the time when the first half of the 'A' station was taken over in mid-May, 1956, until the entire station was settled on line at its full rated capacity. The aim is not to explain in detail how various aspects of the commissioning and operating were carried out, but to indicate the relevance of each aspect of the work to the main problem of establishing the value of gas-cooled reactors as generating plants. Specialist authors will, no doubt, in due course prepare papers giving detailed accounts of specific sections of the programme.

The team involved in commissioning the plant was built up on the site during the 18 months before the take-over. As well as recruiting and training staff to operate the station, the operating staff were also responsible for inspection of the installation by the construction branch and contractors, and for the maintenance of clean conditions in the reactor circuit. This is desirable, since, not only would it be impossible for subsequent inspection to check whether the required standard had been maintained, but it would also be well nigh impossible to correct any major deviation from this standard. It was therefore worth while, both as a means of training staff and to simplify and expedite the inspection, to have the operating staff on site earlier than with conventional plant.

Moreover, particularly with such a novel type of plant, a considerable effort was involved in establishing the routines to be adopted to test equipment and bring it on line. Working parties were formed which included representation from the research establishments and the design offices, as well as the operations branch, for working out in detail a suitable programme. As soon as these bodies had settled the method by which any phase of the experimental and testing programme was to be effected, the operations staff were responsible for the detailed planning necessary to ensure that the programme was carried out expeditiously. Without a high degree of preparation it would have been impossible to commission the station to the extremely tight time-table involved.

(2) LOADING

(2.1) To Just Critical Size

As soon as the final acceptance tests on the essential control gear had been completed on the 19th May, charging fuel into reactor No. 1 was started. To simplify the experimental measurements which were to be made when a barely critical reactor had been obtained, it was desirable to ensure that this first critical reactor was cylindrical in shape. It was therefore necessary to do the majority of this loading by hand. The loading went smoothly, and by the evening of the 22nd May a doubling time had been confirmed, which indicated that a critical reactor had been obtained with less metal charged than had been originally expected.

At this stage there was a break in the loading while series of foil irradiations and doubling times were taken to enable the basic parameters of the reactor to be determined. These were needed, not only to check the nuclear calculations, but also to provide a first estimate of the amount of excess reactivity provided. Arrangements had been made to test the effect of channels of both steel and slightly enriched uranium, so that the reactor could be trimmed to the necessary working figure;

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but since the small critical size indicated the probability that there would be more rather than less reactivity than designed in the fully charged reactor, only the effect of steel absorber was measured. Since results of this type of work take a considerable time to evaluate, loading to full size continued while the research departments analysed the measurements obtained.

(2.2) To Full Size

While the reactor had been sub-critical, or just barely critical, it was tolerable to use fast withdrawal of the control rods to expedite measurements. However, as already described by Ghalib and Bowen,* one of the essential safety features of the Calder Hall reactors is a deliberately slow rate of withdrawal of the control rods, so that reactivity cannot be injected at a dangerously high rate. Clearly this safety device had to be reinstated before continuing to charge; and a different technique of carrying out the second stage of charging was necessary to enable this phase to be completed in reasonable time.

This was done by detaching a number of control rods from their mechanisms, so that they remained inserted and unable to be withdrawn throughout the operation, the number being calculated so that the amount of absorber inserted was not enough to keep the reactor sub-critical when fully charged. The remaining rods were held in the fully withdrawn position on the frequency convertors, so that they were available for immediately counteracting any unexpected approach to critical. The charge to full size then took the form of a series of controlled approaches to critical, extra rods being inserted as it was found that the installed ones were being balanced by the build-up of reactivity. This not only shortened the time, by obviating the need to withdraw the main block of control rods, but also gave a more sensitive indication of the progress of charging, since a continual trace of the build-up of reactivity was obtained from

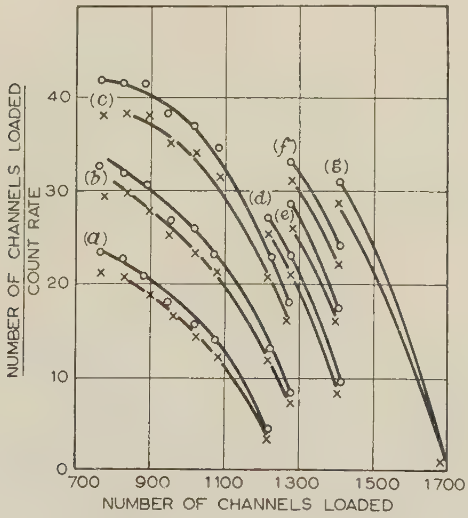

Fig. 1.—Loading to full size: approach-to-criticality curves.

○ Counter No. 2.
× Counter No. 3.

Number of control rods inserted:

(a) 20. (d) 26. (f) 30.
(b) 22. (e) 28. (g) 32.
(c) 24.

the installed counting gear. Fig. 1 shows traces of the series of approaches to critical, including the last one, where at full size the reactor is clearly just being held sub-critical by 32 rods.

To avoid distortion of the approach-to-critical plots, it was still desirable to keep the reactor roughly cylindrical, but this was not such a tight condition as earlier. Most of the loading was therefore done with the charge machines working in their normal groups of 16 channels, or half groups where a complete group caused too large a distortion in the shape.

(3) CALIBRATION AND TESTING

(3.1) Control Rods

By the time the charge to full size was complete, the number of control rods needed to hold the reactor sub-critical in air, and the earlier indication of probable excess reactivity, enabled some indication to be obtained of the control-rod capacity, although at this stage the research departments had not completed their analyses to enable the installed reactivity in air to be known accurately. However, it was clear that the originally calculated 70 rods were not needed, so a revised pattern of 52 control rods was selected with which to carry out the control-rod calibration. This was done by pressurizing the reactor with air, starting from the highest vacuum possible, and balancing increases in air pressure (and therefore of nitrogen absorber) by withdrawing the rods. After each main reading a measurement of the pressure coefficient was obtained by doubling times over a small pressure difference. The main calibration curve having been obtained on the outward run, on the inward run rough confirmation was obtained that the shape of the curve was not markedly dissimilar for small groups of rods, such as the two or four rods which could be selected for fine control. Fig. 2 shows the traces

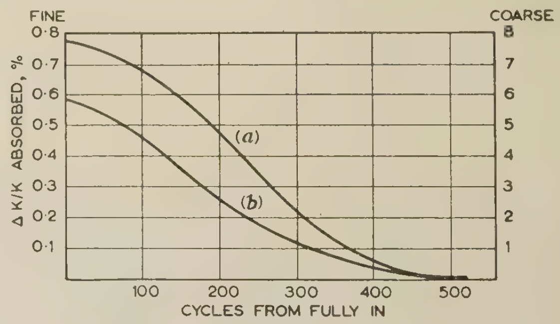

Fig. 2.—Control-rod calibration.

(a) 4 fine rods.
(b) 40 rods.

of the calibration curves obtained, as normalized for final operation.

The establishment of this calibration curve gave a measure of the installed excess reactivity in air as well as of the absorbing capacity of the rods. By now the research departments had completed their calculations; and both sets of results agreed that, instead of the originally expected 4·2% excess reactivity, there would be about 5·6% available when the air had been removed and the reactor pressurized with carbon dioxide. It was therefore decided to trim the reactivity in this state down to 4·5% by adding steel rods, for this left a reasonable amount of reactivity in hand for dealing with the possibility that some of the poisoning coefficients might be larger than expected. With this retrimming of the reactivity of the reactor it was also possible to reduce the number of control rods installed, since a revised pattern of 40 rods was capable of providing 6% reactivity control, i.e. enough to absorb the excess reactivity and provide an additional 1·5% negative reactivity to hold the reactor shut down. In both reactivity and control-rod capacity the main object was to ensure that the reactor would work safely rather than, on this initial run, to trim to the last degree of efficiency.

* Ghalib, S. A., and Bowen, J. H.: 'Equipment for the Control of the Reactor', *Journal of the British Nuclear Energy Conference*, 1957, 2, p. 187.

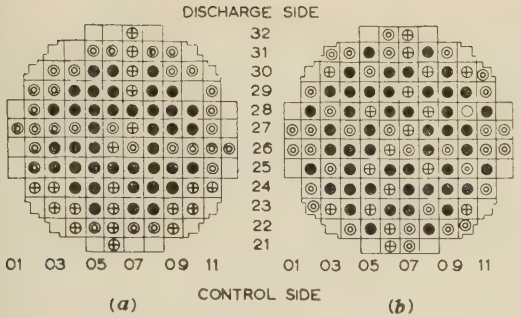

Fig. 3.—Pattern on reactor top.

Equipment in charge tube.
● Control rod.
○ Thermocouple.
⊕ Flux scanner.
(a) Reactor No 1.
(b) Reactor No 2.

The pattern adopted is shown in Fig. 3(*a*). As well as allowing the reactor to commence with ample reactivity and control-rod capacity in hand, the reduction of the number of control rods to 40 allowed extra experimental facilities to be inserted in some of the charge tubes from which control rods had been withdrawn. Additional flux-scanning facilities and thermocouple cartridges were installed to enable a better picture of the performance of the reactor to be obtained.

By this stage in the programme it had been confirmed that the design of the reactor was satisfactory from the nuclear aspect and had ample control capacity installed; furthermore, the indications were that the design was conservative and gave opportunity for development.

(3.2) Mechanical Tests

As soon as the repatterning and trimming had been completed, a start was made on the mechanical testing. Tests had been carried out before the reactor was handed over, but a further check was necessary to ensure that there were no peculiarities about the flow pattern when the reactor was charged. In addition, measurements were taken to verify that the gagging pattern installed gave the predicted gas flows up the fuel-element channels, and to ensure that no obstructions had been left in the course of charging.

After the air-flow tests, which were conducted at atmospheric pressure to ease the problem of moving instruments inside the reactor, the reactor was pressurized with carbon dioxide. In the course of pressurizing a considerable programme of leak tracing and tightening was carried out. Once the degree of tightness was satisfactory, the reactor was fully pressurized and a full-power blower run was started. During this period tests were carried out to ensure that the coolant flows in the four circuits were balanced under varying load and flow conditions. After a 4-day full-power run the reactor was blown down for inspection.

During the blow-down an area survey was made both inside the reactor building and works fence and also outside in the neighbourhood to check whether the release of carbon dioxide might cause any form of hazard. Although the release took place under conditions which encouraged a rapid descent of the gas, i.e. cold gas and temperature inversion, only one of the detecting stations found any significant increase in carbon-dioxide concentration, and this was very much below anything approaching a health hazard. It is therefore safe to assume that, under normal conditions, when the gas is released hot, there is no possibility of any adverse effect in the area, particularly as the atmospheric conditions are normally much more favourable to rapid mixing and dissipation. This is confirmed by experience.

Before the reactor was finally purged and refilled with air for inspection, the opportunity was taken to operate the charge and discharge machines with the full carbon-dioxide purging routine, to establish the time-constants involved and any weaknesses in the equipment. After this the reactor was purged and a full-scale inspection was carried out on the entire gas circuit, which confirmed that the equipment within it was in good condition and mechanically sound.

(3.3) Burst-Cartridge Detection-Gear Tests

The next equipment to be tested was the burst-cartridge detection gear. The test was carried out by irradiating uranium foils in some of the fuel-element channels and measuring the signal produced. An immediate indication was obtained of the very high sensitivity of the equipment provided, but it was also discovered that a high background signal rapidly built up and interfered with its sensitivity, owing to the build-up of argon activity.

This information coincided with the discovery of two other sources of trouble. Maloperation of a valve on one of the blower-seal oil-detraining systems had allowed a considerable quantity of oil to pass into the reactor and this had sprayed over the bottom of the reactor and the central fuel-element channels. In addition, some of the top fuel-element spiders had worked loose during the blower tests and about two dozen had come off, allowing the fuel element to fall to the side of the channel.

A break in the experimental programme was therefore made to allow these three defects to be put right. During the course of the next fortnight arrangements were made for installing a small carbon-dioxide bleed into each of the burst-cartridge precipitators to keep the detecting chambers clear of active argon. At the same time a small production line was laid down at the top of the reactor to enable improved locking arrangements to be installed on all the 1 696 top cartridges, for a quick check of several complete channels indicated that it was only the top spider, where there was no cartridge above to hold it down, which was working loose. Detachments were also deployed inside the bottom of the reactor for cleaning out the oil which had been injected. By the end of the period satisfactory solutions to all three problems had been achieved, although clearly a considerable amount of the oil contamination on the fuel elements themselves could not be totally removed.

The purge of the burst-cartridge precipitators was completely adequate for its task, and a further test quickly indicated that the background could be held to a very satisfactory level, so that full advantage of the sensitivity of the equipment could be taken. This is particularly important at Calder Hall, for an immediate indication of a burst not only prevents activity being recirculated and spread round the circuit, but also enables the circuit to be kept at an extremely low degree of contamination, so that maintenance of parts of it lying outside the reactor remains reasonably easy to carry out.

As soon as these tests had been completed a final inspection of the reactor circuit took place, the last special cartridges were charged and the circuit was sealed down, evacuated to remove the air and recharged with carbon dioxide ready for power operation.

(4) POWER OPERATION

(4.1) Thermal

Before the reactor was allowed to operate under its own power, it was first heated by injecting steam into the heat exchangers and warming the whole circuit by circulating carbon dioxide.

This enabled a measurement of the temperature coefficient of the reactor to be obtained and also, over a very short range, gave a check of the control-rod calibration in the hot condition, so that some indication could be obtained whether it was markedly different from the calibration when cold. As soon as this had been completed, the reactor was allowed to work up to power, passing all the steam initially to the dump condenser. As the power was raised, measurements were made to establish the xenon coefficient, and at a low power the reactor was held while safety valves were floated and the automatic tripping devices were given a final full-scale check. However, since the reactor was operating extremely smoothly, some of the intermediate halts and hesitations were abandoned, and it was allowed to go up to about 130 MW with a top can temperature of 350° C and settled there while the operators familiarized themselves with the normal operating conditions. At this stage complete radiation surveys over the reactor were carried out to establish whether the shielding was adequate in all positions. Additional shielding was installed in the few places where the levels were higher than tolerable, so that the level in all working areas was well within the accepted limits. This is particularly important at Calder Hall, since one object of the design was to maintain conditions so that the operators could live and work at the plant as in a normal industrial occupation. In fact, messrooms are provided for the operators on the reactor itself, because the level of radiation and contamination can be held to a negligible figure.

(4.2) Electrical

Since the steam side of the reactor was functioning smoothly, there was no particular advantage in delaying commissioning the turbo-alternators, so No. 1 set was run up during the third week in August, and after the usual tests was paralleled at 10.25 p.m. on the 27th. As soon as this had been settled on line, No. 2 turbo-alternator followed, and No. 3 was also run up and commissioned as a spare. Since the opening ceremony was then only about a month away, the reactor was left settled at about 136 MW (heat) producing 28 MW (electricity), rather than immediately trying to push it up to full rated power.

By now it was clear that the pattern of control rods which had been chosen and the excess reactivity left installed, which necessitated running with the rods inserted a considerable distance into the core, were giving a bad flux-distribution pattern. The mass of absorber concentrated towards the centre of the reactor was making the central channels run much colder than normal and this was reducing the thermal efficiency of the plant. Figs. 4(*a*) and 5(*a*) show flux and temperature plots across the reactor at this stage and indicate the serious flux and temperature depressions which were causing the low efficiency. Attempts were made to improve the pattern by running with some of the outermost control rods fully inserted into the reactor, but these were neither far enough out radially nor uniformly enough distributed. It was decided that no attempt should be made to alter the trim until after the official opening, and the reactor was left working under settled conditions while the entire staff familiarized themselves with the operating routine.

During this period a small number of unscheduled trips occurred, arising almost equally from defective components and maloperation during maintenance of the essential safety circuits, which fail to safety. In view of the considerable complexity of the instrumentation and control circuits, this number was very satisfactory.

(4.3) Full Power, Reactor No. 1

Immediately after the official opening by Her Majesty the Queen on the 17th October, the reactor was taken up to full power. On this occasion, owing to the cold centre, it was found that only about 170 MW of heat could be extracted, even with full blower speed. However, the metallurgists had already asked for a shut-down in early November, to enable a small amount of experimental fuel to be discharged to measure the rate of bowing of the fuel elements, and it was then agreed that advantage would be taken of this opportunity to retrim the reactor, to enable the rods to be further withdrawn and reduce distortion of the flux pattern.

When the reactor had been shut down the experimental channels and a small number of ordinary fuel elements were withdrawn, the latter to be replaced by steel to reduce the excess reactivity. This operation gave a useful test of the charge and discharge gear, particularly when awkward conditions were experienced, owing to sticking between cartridges—caused, as was discovered later, by the oil which had been injected earlier. As a result of experience during this discharge, arrangements were made for improving the visibility on the discharge machines so that the exact nature of any trouble being experienced could be rapidly ascertained. In addition, the need for special grappling facilities for dealing with trouble inside the reactor was shown; and arrangements were put in hand for providing not merely viewing facilities, but facilities which carried with them special tools for dealing with damaged cartridges. However, despite the trouble in withdrawing some of the fuel elements, a very welcome indication was obtained that the discharge routine did not cause contamination of the charge floor and that comparatively simple control methods were sufficient to protect the operators fully from any hazards which might exist. Moreover, since the entire cycle in the reactor is carried out dry, it was found that cleaning up the reactor charge floor with dusters and vacuum sweepers was simple when the operation was over, so that unrestricted access could once more be allowed.

As a result of retrimming the reactor it was possible to withdraw the rods further and improve the temperature distribution a little. This enabled the fully rated output of the reactor (180 MW) to be achieved; but it was still at a low efficiency, since the low output temperature (311° C) and full blower power needed considerably reduced the thermal efficiency of the station. On the other hand, experience acquired when it was necessary to take the reactor off line for work on separate parts indicated that the flexibility of this form of reactor was much greater than was originally hoped. By working the reactor as a constant-temperature-difference device and matching the load changes to variations in coolant flow, it had proved possible to put on or take off load from the reactor as smoothly and quickly as on the associated turbo-alternator sets.

Immediately after the shut-down the first burst was detected on the burst-cartridge-detection gear. The trace indicated that the apparatus gave ample warning and that the rate of increase of activity allowed plenty of time to dispose of the burst satisfactorily.

(5) REACTOR No. 2

In the meantime, the construction branch had been finishing reactor No. 2, the other half of Calder Hall 'A' station, and its precommissioning tests were complete and the reactor handed over by the end of November. During December, therefore, an intense experimental programme was carried out on reactor No. 2 to clear up some of the doubts and gaps in information left by the commissioning of reactor No. 1. In the main this work was concentrated on providing additional experimental data for reactor-physics calculations, by measurements on different shapes and sizes of charged reactor core, to enable the reason for the $1\frac{1}{2}\%$ error in the original estimate of installed reactivity to be explained. While an accuracy of this order was a very

creditable achievement by the physicists with the amount of information available before Calder Hall was designed, clearly this amount of excess reactivity was expensive to install and an improvement in the methods of calculation was a most desirable objective. In addition, a considerable amount of work was done in varying the size, number and pattern of control rods, so that a more accurate understanding of their control capacity was obtained.

As a result of the additional information obtained from the first run of reactor No. 1 and during this experimental phase, reactor No. 2 was trimmed more closely to the correct initial excess reactivity. This was associated with a revised pattern of 48 control rods, as shown in Fig. 3(*b*). It will be seen that these are more uniformly distributed and therefore cause less distortion in the reactor flux; and since the revised pattern also provided a greater excess of control-rod capacity over installed reactivity, the safety of operation of the reactor had been improved as well as its efficiency. It was already realized that some modification to the gagging pattern might also be needed to deal with the cold central region, but it was impossible for the revised gagging calculations to be completed in time for them to affect the charging of the second reactor.

After the experimental physical work had been completed it was agreed that the mechanical tests could be considerably shortened in view of the experience of commissioning and running reactor No. 1. The reactor was therefore ready for working up to power by the beginning of February. It was then put on line and taken up to full power, only pausing for a few days at one or two intermediate points while experimental work in connection with the carbon-dioxide/graphite reaction was carried out.

When full speed on the blowers had been achieved, it was found that the improvement in trim and control-rod pattern had enabled the reactor to be run well above its rated capacity; but, even so, the outlet temperature was only about 320° C. The efficiency was therefore still below the design figure, and it was now clearly confirmed that a modification to the gagging pattern was needed to correct this.

(6) FIRST RECHARGE, REACTOR No. 1

By now, investigation of the experimental cartridges discharged in November had confirmed the predictions on bowing and indicated that an improved cartridge to prevent this bowing was necessary. It was therefore decided to make the first discharge a complete recharge of the reactor with braced cartridges, and to take advantage of this to modify the gagging and control-rod patterns to improve the efficiency of operation.

By the end of the run three bursts had been experienced, two of which had been removed. The third was building up so slowly that no special arrangements were needed, and it was discharged with the main weight of metal. Moreover, since a complete recharge had been agreed, it was decided to arrange a full-temperature run before shut-down to confirm the steam capacity of the circuit, by running the cartridges above their rated temperature. This was carried out successfully, and indicated that the turbines would be capable of handling considerably more than the specified quantity of steam. In addition, instead of discharging immediately after shutting down, arrangements were made to allow the reactor to de-poison at a high temperature and then to be reduced to atmospheric temperature, to enable accurate measurements to be made of the xenon and temperature coefficients with the partly irradiated charge. This was necessary to establish the effect of the build-up of plutonium on the total excess reactivity, both in the hot and cold condition, to ensure that ample control-rod capacity was still being held.

As soon as this experimental work was clear and the reactor could be opened up, a considerable inspection and maintenance programme was put under way while the actual recharging took place. Two of the heat exchangers were thoroughly inspected and the cover was taken off one of the blowers. In the latter case, the surface contamination was negligible and, being dry, was very quickly disposed of, while access to the heat exchangers for internal inspection was carried out quite successfully with airlines, since the only hazard was caused by the dust which the inspection inevitably raised. At the same time, steel and graphite specimens were extracted for examination by the research department and all the essential services and valves were serviced.

Modifications were also carried out to the shielding to improve the radiation levels further, while a modified oil-detraining system was installed to reduce the possibility of injecting oil into the reactor circuit.

During the discharge the value of the modifications introduced to improve the visibility of the discharge machines and the additional remote-handling techniques developed was fully proved, since considerable trouble arose from sticking between elements in those zones where the oil contamination had been serious. Where this problem did not arise the routine operated smoothly. Moreover, the extended trial given to the machines during a complete discharge was a most effective method of showing up any weak links in the system. Some modifications were put in hand to improve their performance, so that by the end of the discharge a smooth and steady operation of the cycle was in action, when not bedevilled by stuck cartridges.

Experience during this discharge confirmed how much could be achieved, even inside the reactor, by remote-handling devices and gave some extremely useful experience and development opportunities, so that suitable tools are now available for a wide range of special functions. In addition, this much larger and longer discharge further confirmed the cleanliness which could be achieved on the charge floor, indicating that the cycle of operations could be carried out without the operators being subjected to high radiation levels or any serious risk of contamination being carried on to other parts of the reactor. Moreover, on the reactor charge-floor itself, as soon as the operation was completed it proved possible to clear up such minor contamination as had been caused and leave the floor once again clean and available for unrestricted access.

(7) CALDER 'A' AT FULL POWER

As soon as the regagging, repatterning and recharging had been completed, reactor No. 1 was put back on line and taken straight up to full power. This was achieved with ample spare blower power in hand and control on the low-pressure boiler, as the outlet temperature had been raised by the revised gagging and control pattern to 330° C—a figure which revised design calculations indicated was the maximum to be expected. Fig. 6 shows a flow-sheet for the station under these conditions; and Figs. 4(*b*) and 5(*b*) indicate the improvements in flux and temperature pattern which give the improved results on reactor No. 1. The reactor is now clearly working at full design capacity and efficiency with a fair amount of capacity in hand.

(8) EXPERIENCE

To sum up, therefore, the experience of operating Calder 'A' (the original Calder Hall project): not only has the main object of confirming the technical feasibility of this type of nuclear reactor been achieved, but an indication has been obtained that the design was conservative and could be considerably extended. The additional reactivity now known to be available could be invested, as in the C.E.A. stations, in considerably increasing

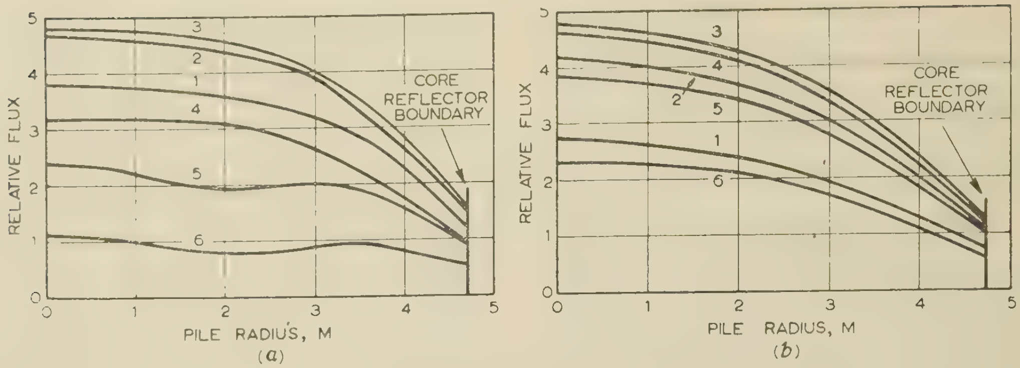

Fig. 4.—Radial flux distribution in planes through centre of cartridges.

(a) 136 MW: control rods at 306 cycles; initial pattern.
(b) 180 MW: control rods at 500 cycles; revised pattern.

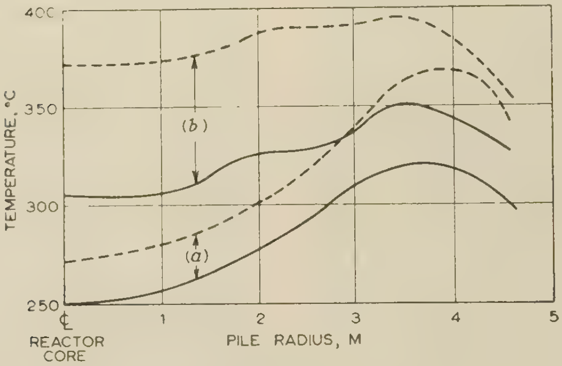

Fig. 5.—Radial temperature distribution.

- - - - - Temperature of top cartridge.
——— Gas outlet temperature.

(a) 136 MW: control rods at 306 cycles; initial pattern.
(b) 180 MW: control rods at 500 cycles; revised pattern.

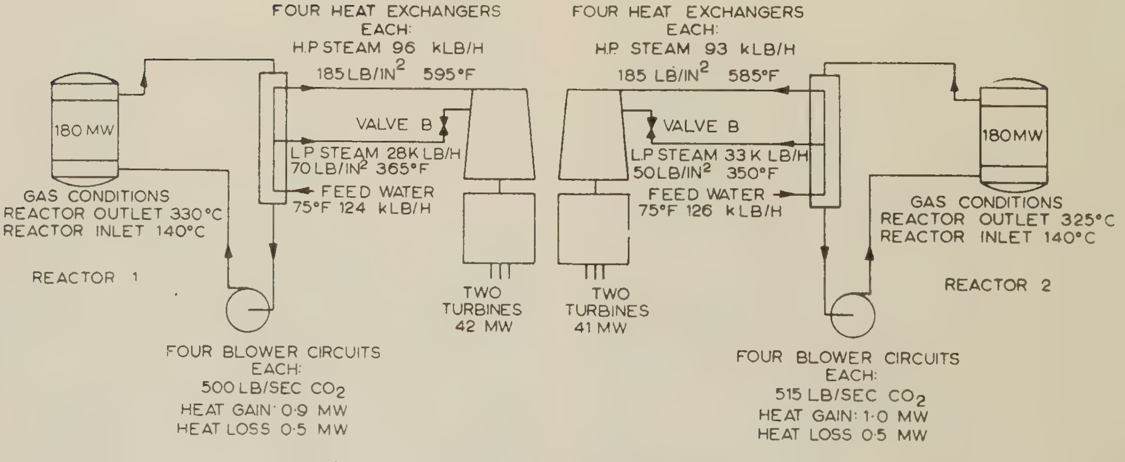

Fig. 6.—Heat flows: Calder Hall at full power.

output from a given size of reactor or could enable a smaller reactor of this type to be designed where a larger amount of power cannot be absorbed. The project has also shown that the standards necessary in nuclear engineering, although high, are far from impossible. Particularly on the reactor circuit, the standards of clean conditions to be maintained are considerably higher than in normal industrial practice; but with adequate inspection and supervision and careful planning of the work, they are readily achievable. In addition, the degree of reliability needed from equipment used in or with nuclear reactors is clearly very much higher than normally expected; but the evidence is that, given adequate time and effort in development and testing, this also can be achieved. While the original pattern of cartridges has needed modification to deal with the bowing effect, these are now quite satisfactory for irradiation under the Calder Hall conditions. Clearly, fuel elements will always be a limiting factor in the efficiency and reliability of reactors, because as fast as any improvement is made in their

qualities, the design engineers will take advantage of it to increase the efficiency or the rating of the plant.

With regard to the economics of operating nuclear reactors, it is not yet possible to extract an accurate picture of the probable future trends from the Calder Hall units, for until the station is complete and the normal operating cycle in progress, the initial effort required for commissioning and testing is clearly distorting the picture. Moreover, the very marked differences between Calder Hall and a power station designed primarily for power production make translation of any figures particularly difficult.

So far as the safety of this type of reactor is concerned, the operation of Calder Hall to date has confirmed that it is a remarkably stable and safe plant. Further experimental work is in progress, but every indication confirms that nuclear reactors of this type can be accepted as no more of a hazard to their operators or the neighbourhood than other large-scale industrial plants. The standard of cleanliness achieved on the plant has been most satisfactory; and even after a discharge, the small amount of contamination which may have been released has been very easily and quickly cleaned up. Under normal working conditions the radiation and contamination backgrounds on the plant are negligible, so that the original concept of living and feeding on the plant has proved quite satisfactory. Experience with the release of the carbon-dioxide coolant either as leakage or during normal operating conditions has indicated that this produces no problem or danger either to the operators or to areas outside the plant. The leak rate has been quite reasonable when consideration is given to the fact that the circuit was designed to good steam standards. Clearly this can be, and is being, improved; but the problem is a purely economic one, since it introduces no operating or safety consideration.

So far as the normal operating routine is concerned, the station has worked smoothly right from the start. Working-up and changing conditions have proved as straightforward and simple as on a conventional plant. Moreover, the flexibility of the station has proved to be greater than originally thought over most of its operating range. While working up from the fully shut-down condition is slow, owing to the time taken to run out the control rods and heat up the system, load changes between 15% and full load can be effected extremely easily and quickly. This feature is already of value in making equipment available for maintenance, and clearly has a marked bearing on the usefulness of nuclear power stations in conditions where their entire output cannot always be absorbed as base load. Moreover, experience has indicated that availability and accessibility for maintenance is better than was originally expected. Considerable portions of the reactor circuit can be made available for routine maintenance, owing to the ease with which part-load working and isolating of separate circuits can be achieved, and during main discharges the accessibility of the circuit outside the actual reactor core is good enough for the normal routine inspections and maintenance to be carried out. Within the reactor itself, monitoring by installed specimens is giving an adequate indication of the state of the reactor and its enclosing vessel, while steady development of remote handling and viewing devices enables a large range of tasks inside the core to be carried out satisfactorily.

(9) ACKNOWLEDGMENT

The work described in the paper was clearly a co-operative effort by a team which included members from many branches and establishments of the United Kingdom Atomic Energy Authority and other interested organizations as well as the Calder Hall works staff. The author wishes to thank the Managing Director of the Industrial Group for permission to publish the results of their efforts, and to acknowledge the contributions of all who helped to achieve them.

DISCUSSION BEFORE A MEETING OF THE SUPPLY SECTION HELD IN CONJUNCTION WITH THE BRITISH NUCLEAR ENERGY CONFERENCE, 16TH APRIL, 1958

Mr. R. A. Peddie: There have been a large number of well-deserved tributes paid to the design staff of this outstanding project, and now a tribute can be paid to the operational staff under the author, who had the onerous task of putting this large prototype plant to work. This task was not made any lighter by the presence of numerous senior engineers from industry and the Central Electricity Generating Board who were nominally under training.

I agree with the author's deprecation of the tendency to consider nuclear engineering to be a new subject and not a new application of known techniques.

Appreciating that any comment must be based on a small amount of data and experience, I should like additional information upon the following points.

One of the objectives was to gain knowledge of the accessibility of the plant for maintenance and inspection purposes. Has any experience yet been obtained? The Sections concerning calibration and mechanical testing are self-explanatory, except the statement in Section 4.1 that the safety valves were floated. How was the l.p. safety valve set? Towards the end of this Section a reference is made to the level of radiation and contamination in working areas being kept within acceptable limits, and later, that contamination was negligible. The value of the paper would be enhanced if numerical values were given.

Maloperation and defective components are referred to in Section 4.2, and it is stated that the number of unscheduled trips was divided equally between these two items. Considering the first, were the safety trip circuits so segregated that the maintenance fitter could not cause an unscheduled trip simply by his screwdriver slipping, i.e. were these trips genuine maloperation or bad design? I am not surprised that unscheduled trips attributed to defective components occurred, having seen an open multi-point recorder on the concrete floor of the control room during installation. How many defective components were due to manufacture and design, and how many to bad installation?

The paper gives the impression that the burst-slug-detection gear performed extremely satisfactorily. With the experience gained since the paper was written, is this view still held?

Section 8 states that the economics of operating the Calder Hall reactors have been clouded by the commissioning and testing effort. Can the author enlarge on this? Finally, in this Section, has the author given a clue to the problem of two-shift operation in commenting on the flexibility of the plant between 15% and full load?

The author refers to the method of commissioning Calder Hall by committee, the operating staff implementing the decisions of the various specialist bodies. Would he advocate the same system again, or would he make any modifications in the commissioning administration?

Finally, does the author think that there is any case for variable-speed blowers in base-load plants of this nature, and do the operational advantages of a fixed pressure at the l.p. side of the heat exchanger outweigh those of the floating-pressure system installed at Calder Hall?

Mr. R. F. Jackson: I am impressed by the way in which the

Calder Hall reactor behaves as a constant-temperature box: by varying the gas flow through it one varies the heat output at constant temperature. This depends mainly on the temperature coefficient of reactivity of the metal, and I wonder how such a reactor would behave if this reactivity coefficient were not so marked. This is a problem with which one might be faced in future reactors.

One of the problems which has been present in all the reactors from Bepo to Windscale and Calder Hall has been measuring fuel-element temperatures. We know how to do this, but it is quite a complicated business, requiring long thermocouple leads. Is it now felt that measuring gas outlet temperatures only would be an adequate guide to changing conditions, such as the change in flux over the reactor core during operation?

I understand that many of the reactors at present being considered will have loading and unloading equipment which will operate while the reactor is on load. Has the author any general points of advice to designers of such equipment? I think it has been true that the operational engineer has very strong views on the simplicity and ruggedness with which loading and unloading equipment should be built, rather than designing into it too much mechanical ingenuity. In the latter case, the correction of a mechanical breakdown may be very much more difficult in an equipment containing several thousand curies of activity than it would be in a non-active machine such as a piece of boot-making machinery which can readily be taken to pieces and reassembled.

Dr. J. Shaw: During the commissioning and operation of both Calder Hall reactors a great deal of experience has been obtained on the ease and effectiveness of retrimming the radial neutron-flux distributions. The particular pattern of the 40 control rods used for the first reactor resulted in considerable flattening of the radial flux distribution, with a resultant central region of low temperature. Even after repatterning the control rods and hence reshaping the flux it was still found necessary to regag in order to obtain the design gas outlet temperature of 330° C. The experience obtained in connection with the regagging of the core and reshaping of the flux distribution would be useful to those at present considering the problems involved in commissioning the civil power reactors. If the theoretical flux distributions are not realized in practice, the question of whether to repattern the gags to the experimentally determined flux or to gag to a theoretical distribution and then reshape the flux must be considered. The latter is preferable from a practical point of view, the remaining difficulty being the effectiveness of reshaping flux distributions with absorbers. I should appreciate the author's views on this question.

The tests carried out during the commissioning of the two Calder Hall reactors and outlined in the paper, were, as stated by the author, to indicate the technical and economic feasibilities of the reactor, to confirm the reactor's safety and to establish the limitations of this kind of reactor. In the light of the experience gained with the first two reactors, does the author consider it essential to carry out as exhaustive a programme of tests on the other identical reactors, such as the third and fourth units and Calder Hall and those at Chapel Cross? Will it be possible to reduce considerably the commissioning period with these reactors by carrying out only a few essential tests? If so, which tests does the author consider to be most essential?

Mr. D. Bolton: There is a considerable difference in scale between the reactors for Calder Hall and the C.E.G.B. stations. Compared with Calder Hall, a typical C.E.G.B. reactor will have twice the quantity of uranium, twice the number of channels and at least three times the output. In view of these figures, does the author recommend any changes to the general procedure described in the paper which would apply to the commissioning of the C.E.G.B. stations? If the same procedure were adopted, would it be necessary to extend the commissioning period to cope with the increased number of channels? Lastly, what proportion of the commissioning time for the C.E.G.B. stations ought to be devoted to determining nuclear parameters, so that future stations can be designed with greater accuracy?

Mr. G. C. Allingham: What features in the design of a reactor intended essentially for plutonium production would markedly influence the design to the prejudice of its efficiency as a generator of electricity? What would be the marked difference between a plant optimized for plutonium and one primarily designed as a power producer, and what distorting effects would such differences have on the economics of operating the station?

If the reactor had been primarily designed as a power producer, in what way would the design have been different from its design as a plutonium-producing unit?

After it was decided to develop reactors of the Calder Hall type for the definite purpose of power production, various improvements have been made in the original designs which have increased their efficiency as generators of electricity; but I cannot see that any of these improvements arose from the fact that the reactor was originally designed for plutonium production. For example, the size of the core was increased because it was found possible to construct pressure vessels of thicker steel plate.

Major W. V. G. Fuge: What is the reason for the difference in the distribution of the control rods in the two reactors?

Mr. W. J. Prior: Why is there no reference in the paper to the staff organization at Calder Hall, which presumably was determined a long time ago? Having been involved in setting up that organization and having worked with it, is the author satisfied that it is correct or does he think that it could be improved in any way? What are his ideas on the training of his engineering personnel and technical staffs and the manual workers who normally operate and maintain the plant?

Mr. K. P. Gibbs: The paper states that at one stage during the commissioning a considerable quantity of oil entered the reactor by mistake. The original design of the control mechanism and other mechanisms was based on the assumption that no oil must be allowed within the reactor. Yet after this accident, apart from the sticking together of fuel elements, no bad effects resulted. Does this mean that in the author's opinion, provided that it is certain that adequate precautions have been taken to prevent the ingress of oil in bulk, the complete embargo on oil can be removed and mechanisms should be lubricated or greased both in order to reduce corrosion and also to reduce wear?

Mr. S. H. Wearne (*communicated*): As power stations, the developed Calder Hall nuclear types are at present dominated in design and operation by the reactor and steam-raising parts to a far greater extent than in fuel-fired plants. This and the concentration of plant on two reactors result in three control rooms at the station of nearly equal importance, one in each reactor and one in the turbine hall. In view of the interdependence of controls and the novelty of nuclear station commissioning, did the author ever wish all controls were centralized in one room, with additional safety as well as convenience to set against the extra cost of such a scheme? With larger reactor and turbine units the power cost of such centralization improves, and it is interesting to note its recent adoption for a 2-set station at Rogerstone.

From experience so far has it been suggested that the amount of instrumentation at Calder Hall would be excessive on civil reactors, considering not cost—over which safety must take priority—but the effect on safety which elaboration invites through confusion?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. K. L. Stretch (*in reply*): On Mr. Peddie's inquiry about radiation, more important than the exact figures—which will no doubt be released in time—is the indication that it is not unduly difficult or expensive to maintain safe working conditions if the correct design criteria are used. As in other safety problems, areas of unrestricted access must be held to levels well below the safe permanent exposure figure. Apportionment of responsibility for failures of the control system between design, installation and operation is not an exact science; and it is, of course, important for the designers to ensure that the system can be maintained without exceptional skill or techniques. At Calder Hall a very creditable solution was provided which was not unduly difficult to operate and gave as good a picture of what was happening as could be expected at this stage.

The activities of the commissioning working parties must be taken as supplementary to, rather than conflicting with, the normal operational responsibility of the works management. Provided that this position is clearly understood, a committee which brings a wider range of experience and knowledge to help the operators commission the station can be, as in this case, of the greatest assistance if properly managed.

The necessity for variable-speed blowers depends mainly on how often the station will be working on part load. It is essential to trim the gas flows accurately to keep the gas temperature correct, but this could be achieved by simpler methods if the station is nearly always working at full load.

While appreciating Mr. Jackson's remarks about the mechanical difficulties of fuel-element-temperature measurement, the gas temperatures alone are not sufficient to determine the flux and temperature patterns over the reactor core. Knowledge of temperature conditions inside the reactor is still inadequate. Sufficient indications are available to enable the reactors to be run with reasonable safety if they are intelligently used, but much more is needed if these conditions are to be maintained when the reactors are trimmed and driven to their economic limits.

His warning of the more difficult control problems which will be involved in operating reactors which do not have the negative temperature coefficient associated with the present Calder Hall conditions is timely, as are his comments on the problem of charging and discharging on load. Extensive inactive proving is essential, since only rigorous service testing will eliminate all weaknesses in mechanical design. As well as the safety problems posed by any failure of the recharging gear on an operating reactor, such incidents will have a serious effect on the economics of the station.

Dr. Shaw's question about preferring regagging or retrimming to correlate the flux and flow patterns cannot be answered abstractly, but must depend on the particular mechanical details of any given reactor. Until our knowledge of nuclear theory is much greater than at present, the first of each new type of reactor will need a similar commissioning routine to that adopted at Calder Hall. Once its characteristics are established, there is no operational reason why exact copies should not be charged and operated after simpler tests; but it may be that for some considerable time advantage must be taken of every new commissioning to acquire more basic data for nuclear-reactor theory.

Mr. Prior's inquiry about staffing and training merits a separate discussion. The most important lesson was the need for close co-operation at every level. The main danger is for specialist differentials to be carried too high, resulting in lack of understanding and co-operation and providing the opportunity for trouble. Maintenance and safety are not separate functions, but only aspects of the single problem of operating the station; and the main concern in creating a safe and efficient organization must be to ensure that the management have unified and effective control. The complexity of nuclear power plants and the consequent need for a considerable number of specialists on the station makes this even more important.

With regard to training, nuclear power stations present no more formidable problems than any other form of plant. Apart from a very small number of specialists, engineers adequately qualified and experienced in handling other forms of plant can rapidly master the peculiarities of nuclear stations. With a course such as that at Harwell to master the fundamentals of reactor technology and some months of experience of nuclear conditions, any competent engineer should be capable of operating a nuclear station when he has had time to master its own engineering peculiarities. The key problem is the quality of the engineers selected rather than the mysteries of nuclear engineering.

While Mr. Gibbs is correct that some relaxation in allowing lubrication of parts of the reactor circuit is probably possible, there is need for considerable discretion. He dismisses the problems posed by sticking between the elements too lightly.

Mr. Wearne's comments on control rooms are completely valid, as the distribution of control functions over a large number of control rooms is one of the major operational disadvantages at Calder Hall. The tendency to look on reactors and their associated steam-raising and electrical units as a series of unit processes is most misleading, since the system must be operated and controlled as a single integrated unit. With regard to the standard of instrumentation, it must be accepted that higher levels will be needed on nuclear reactors than on conventional boiler plant. This applies particularly to the commissioning and early running phases. When this has been completed, there is much to be said for reducing many facilities to potential indications available for when trouble arises, and permanently recording only a smaller number of key operating figures.

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THE GENERATION OF ELECTRICITY IN THE LONDON AREA

By H. V. PUGH, M.I.Mech.E., Member.

(*The paper was first received* 8*th June, and in revised form* 21*st August*, 1957. *It was published in November*, 1957, *and was read before the* Western Centre 10*th February, the* North-Western Centre 1*st April, and* The Institution 24*th April*, 1958.)

SUMMARY

The paper is complementary to the survey paper by Irving, presented to The Institution in May, 1955.

It attempts to present a picture of the generation and main transmission plant and equipment which existed in London on the 1st April, 1948, and briefly describes new plant and equipment commissioned and planned since that date.

The paper shows the economies which have resulted from bringing together under one control the power stations in the London area.

Reference is also made to fuel supplies, ash disposal, atmospheric pollution and general administrative matters.

(1) INTRODUCTION

When the electricity supply industry was nationalized in 1948, the British Electricity Authority, as it was then known, created 14 Generating Divisions as management units, which were to be responsible to the Authority for the generation and bulk transmission of electricity. Under the Electricity Act of 1947,[2] 14 Area Boards had been established throughout the country, and the Electricity Authority decided that these Divisions should be complementary to, and cover, in the main, the same territories as the Area Boards.

Owing to the amalgamation of the Merseyside and North Wales Division with the North Western Division, the number of Divisions was reduced to 13 in April, 1954. They were further reduced to 11 in 1955 when the Electricity Re-organization (Scotland) Act was passed. Under this Act the two Scottish Divisions were vested in the South of Scotland Electricity Board and at the same time the title of the Authority was changed to the Central Electricity Authority. For simplicity, the term 'Central Electricity Authority' will be used throughout the paper.

The supply of electricity in London has been adequately dealt with in the paper by D. B. Irving.[1] This also briefly surveys the common history of electrical generation and distribution within the boundaries of the London Electricity Board. The historical aspect of the subject, which has been fully covered by a number of valuable papers in the past, among which are References 10, 11, 12 and 13, has not therefore been included. The purpose of the present paper is to provide a complementary survey of the generating plant and main transmission system which is vested in the London Division, and the developments carried out between 1st April, 1948, and 31st December, 1956.

(2) GENERATING PLANT VESTED IN THE LONDON DIVISION ON 1st APRIL, 1948

(2.1) General

The generating stations taken over by the Authority on the 1st April, 1948, are shown in Fig. 1. The total installed capacity vested in the Division amounted to 2 697·511 MW. Of the 30 steam stations, 19, mainly older and smaller plants and having a total installed capacity of 963·366 MW, were owned by local authorities; while the remaining 11 stations, with a total installed capacity of 1 734·145 MW, were owned by four companies.

Mr. Pugh is with the Central Electricity Authority.

The largest station which vested was Battersea with a capacity of 345 MW; and the smallest was Ilford with a capacity of 3 MW. Eight of these stations had installed capacities exceeding 100 MW of which, after Battersea, Barking 'B' with 303·5 MW and Fulham with 300 MW were the largest. No less than 15 of the stations had installed capacities of 50 MW or less.

(2.2) Turbo-Generators

It will be seen from Table 1 that only a small proportion of the total plant which vested in the Division was of modern design. Of the 146 turbo-generator sets acquired, only 11 were less than ten years old. Of the 16 sets operating at pressures of 600 lb/in^2 and over, ten had been installed for more than ten years.

Table 1

Steam Turbo-Generator Sets vested in London Division at 1st April, 1948

(Excluding separately-driven house service sets)
Grouped according to size, working pressure and age

Commissioning year ..	1938–1948	1928–1937	Before 1928	Total numbers	Percentage of total
Age in years	10 or less	Over 10 Under 20	Over 20		
Size groups					%
10 MW and under	—	12	62	74	51
11–20	—	7	25	32	22
21–40	7	16	3	26	18
41–60	2	4	—	6	4
Over 60	2	6	—	8	5
Total numbers	11	45	90	146	100
Pressure groups lb/in^2 (gauge)					
Under 250 ..	—	12	67	79	54
250–400	5	23	23	51	35
600	3	10	—	13	9
1 300 and over ..	3	—	—	3	2
Total numbers	11	45	90	146	100

Total installed capacity of sets: 2 697·511 MW

Advanced steam conditions:
Battersea 'B': One 100 MW set
Pressure: 1 350 lb/in^2 (gauge)
Temperature: 950° F
Taylors Lane high pressure: Two 32 MW sets
Pressure: 1 300 lb/in^2 (gauge)
Temperature: 950° F

Although 73% of the sets had capacities of 20 MW or less, the Division also took over the eight largest generating units in the country, namely one 105 MW set, one 100 kW set, four 75 MW sets and two 69 MW sets.

The majority of the generators were wound for 6·6 or 11 kV, but three stations contained generators wound for 22 kV, and at Taylors Lane two were wound for 33 kV.

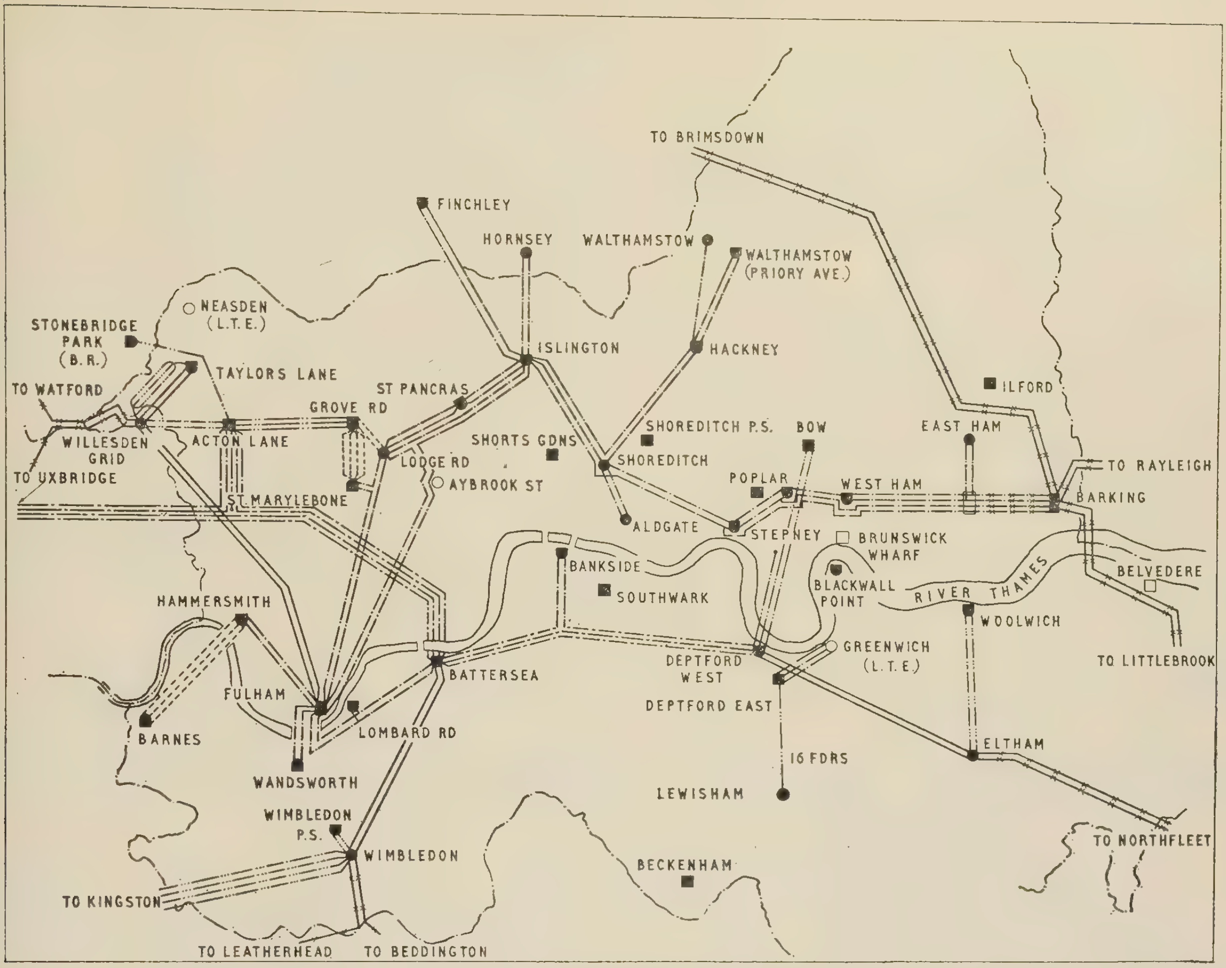

Fig. 1.—Generating stations and transmission system vested in the London Division.

■ Generating station.
● Transforming station.
☗ Generating and transforming station.

	Overhead lines	Underground cables
132 kV	—×———×———×—	—————————
66 kV	—×—·———·—×——	———·———·——
33 kV	—×—··————··—×—	——··——··—
22 kV	—×—·—×—·—×—	——·——·——
6·6 kV		— — — — — —

(2.3) Boilers

Particulars of size, working pressure, and age of the boiler plant are given in Table 2. It will be seen from this Table that 325 boilers were taken over, and that these were spread over wider ranges of age and capacity than the turbo-generator sets which they supplied.

At vesting date, two examples of hand-fired boilers survived at Hammersmith and Ilford, and, at the time of writing, the chain-grate-stoker hoppers at Beckenham are still filled manually.

The chain-grate stoker predominated, and the evolution of this type of firing can be traced from the various installations found in the Division.

There remain in service some interesting examples of early pulverized-fuel-firing equipment. Two 45 klb/h pulverized-fuel boilers were commissioned at St. Pancras in 1922, and are still in operation. Although ten 150 klb/h pulverized-fuel boilers were commissioned in Barking 'A' Station in the years 1928, 1929 and 1930, and small plants were installed at Stepney, Taylors Lane and Watts Grove, there was no large-scale adoption of this method of firing in the London area during the decade which followed the installation of the pioneer plant at St. Pancras. In fact, after 1931, no pulverized-fuel-fired boilers were commissioned in any London station until 1951.

The lapse of interest in pulverized-fuel firing was in a large measure due to the vast improvement made in the design of chain-grate stokers, and the development of the retort stoker. It is also significant that the beginning of the 1930 decade coincided, approximately, with the peak period of a buyers' market in coal. The purchasing of coal to tight specifications was therefore possible, and this reduced the incentive to adopt new methods.

The two outstanding examples of retort-stoker-fired boilers, commissioned during the 1930's, were the six 312 klb/h and three 375 klb/h units at Battersea; and the eight 260 klb/h units at Fulham.

(2.4) Switchgear

The majority of generators were wound for direct coupling to the main busbars, and thus 17 stations operated at 6·6 kV and four at 11 kV; but as the demand for electricity in the London area grew, voltages of 22, 33 and 66 kV were adopted at certain stations.

The standard frequency was 50 c/s, with the exception of Deptford East, where at vesting date a 25 c/s supply was given to the Southern Railway electrified system, a 33 MVA frequency-changer being provided at Deptford West to enable the two systems to be operated in parallel. There were also the remnants

Table 2

Boiler Plant Vested in London Division at 1st April, 1948
Grouped according to size, working pressure and age

Commissioning year	1938–1948	1928–1937	Before 1928	Total numbers	Percentage of total
Age in years	10 or less	Over 10 Under 20	Over 20		
Size groups klb/h					%
Under 60	—	13	122	135	42
60–99	—	39	54	93	29
100–174	20	15	11	46	14
175–249	—	14	—	14	4
250–349	16	19	—	35	11
350 and over	2	—	—	2	—
Total numbers	38	100	187	325	100
Pressure groups lb/in² (gauge)					
Under 200	—	2	43	45	14
200–300	—	34	101	135	42
300–450	12	39	43	94	29
600–650	19	25	—	44	13
900–950	—	—	—	—	—
1 400–1 420	7	—	—	7	2
Total numbers	38	100	187	325	100

Total capacity of boilers: 31 343 klb/h
Advanced steam conditions: Battersea 'B': Two 400 klb/h boilers
Pressure: 1 420 lb/in² (gauge)
Temperature: 965° F
Taylors Lane high-pressure: Five 150 klb/h boilers
Pressure: 1 400 lb/in² (gauge)
Temperature: 960° F

of single- and 2-phase supplies to be found in certain areas, two of the largest being West Ham 'A' and Wimbledon, where a fairly extensive 2-phase distribution system still exists.

The switchgear taken over by the London Division, including that installed on the transmission system, amounted to some 1 000 switches, comprising a mixture of ironclad and cellular equipment. Table 3 shows the percentage of each type for voltages of 33 kV and below.

Table 3

Switchgear Vested in London Division at 1st April, 1948
Grouped according to voltage and type

Voltage	Ironclad vertical isolation	Ironclad horizontal isolation	Cellular
kV	%	%	%
33	83	17	—
22	11	37	52
11	—	73	27
6·6	31	33	36

(2.5) Transmission System

After the passing of the Electricity Acts of 1925 and 1926, the generation of electricity in the London area was developed on the one hand by five companies, the London Power Company, the County of London Electric Supply Company, the South Metropolitan Electric Light and Power Company, the North Metropolitan Electric Supply Company and the City of London Electric Lighting Company; and on the other hand, by a number of municipalities. Each company immediately took steps to interconnect its own generating stations by main transmission operating at 33 kV and 22 kV, while in the case of the municipalities the general tendency was to operate their systems independently of each other, and to limit their network voltages to 11 or 6·6 kV. The interconnection of all the main generating stations in London with the national Grid system[3] in the early 1930's was provided by the Central Electricity Board at 132 and 66 kV. At the same time, the London Power Company and the County of London Company were themselves installing superimposed 66 kV systems. The transmission system taken over by the London Division is shown in Fig. 1, from which it will be seen that the majority of the power stations were connected together via the Division's transmission system, only seven being connected to the Division's network via the London Electricity Board's distribution network.

Owing to the difficulties of running overhead lines in urban areas, the greater part of the system consisted of underground cables, of which 41 circuit-miles were operated at 132 kV and 179 miles at 66 kV. The overhead lines more usually associated with the Grid system were found only at the outer stations of Willesden, Wimbledon, Barking and Eltham. The lengths of overhead line involved were 70 circuit-miles at 132 kV and 8 circuit-miles at 66 kV.

In the associated substations and power stations the total transformer capacity amounted to 2 382 MVA, made up of units ranging in size from 10 to 60 MVA, most of which were provided with on-load tap changers. The 234 circuit-breakers were chiefly of the bulk-oil-volume type, four of the 66 kV equipments only being of the small-oil-volume type. The breaking capacity of all transmission switchgear was 1 500 MVA.

(3) GENERATING PLANT INSTALLED SINCE VESTING DATE

(3.1) The Control of Turbo-Alternators (No. 1) Order 1947

The Control of Turbo-Alternators (No. 1) Order of 1947 (Statutory Rule and Order No. 2386)[4] stipulated that all steam-driven sets, of capacities exceeding 10 MW, ordered from the 1st November, 1947, should conform to standard capacities of 30 and 60 MW, except when produced under licence, or for ships, or for export. The Order laid down the steam conditions, stages of feed heating, and the final feed temperature; and it further stipulated that 30 MW sets should have their most economical rating at an output of 24 MW, and that the 60 MW sets should have their most economical rating at full output. This difference reflects the influence of Grid interconnection which enabled the new, larger and more efficient plant to be operated for long periods at its maximum continuous rating.

This Statutory Rule and Order, which was revoked with effect from the 1st August, 1950, did not materially affect the plant-installation programme in the London Division, as shown by Tables 4 and 5. The installation of 30 and 60 MW sets was due to the general preference for this type of plant rather than any effect of the Statutory Rule and Order.

(3.2) Plant 'Directed' before Vesting Date

Prior to the commencement of the original South-East England electricity scheme of the Central Electricity Board, some measure of interconnection of generating stations serving the centre of London had resulted from the creation of the London Power Company as a generating authority for ten electricity supply companies, but it still remained customary for each supply undertaking to own and, subject to overall direction from the C.E.B., to develop, individual generating stations for its own needs.

Table 4

New Plant 'Directed' for installation in London by the Central Electricity Board at 1st April, 1948, but not then in commission

Station	Programme year	Undertaking	Sets: Number of sets and capacity	Sets: Pressure	Sets: Temperature	Sets: Commissioning year	Boilers: Number of boilers and capacity	Boilers: Pressure	Boilers: Temperature	Boilers: Commissioning year
			MW installed	lb/in² (gauge)	°F		klb/h	lb/in² (gauge)	°F	
Bankside 'B' ..	1950	City of London Co.	1 × 60	900	900	1952	2 × 375	950	925	1952
	1950		1 × 60	900	900	1953	2 × 375	950	925	1953
Barking 'C' ..	1948	County of London Co.	1 × 75	900	925	1952	3 × 405	950	940	1953
	1948		1 × 75	900	925	1953	1 × 405	950	940	1954
	1949		1 × 75	900	925	1954	1 × 405	950	940	1954
	1949						*1 × 405	950	940	‡
Battersea 'B' ..	1947	London Power Co.	1 × 60	1 350	950	1951	2 × 425	1 420	965	1952
	1947						1 × 425	1 420	965	1953
Blackwall Point ..	1948	South Met. Co.	2 × 30	600	850	1951	2 × 365	635	875	1951
	1948		1 × 30	600	850	1952	1 × 365	635	875	1952
Brunswick Wharf	1948	Poplar Borough Council	2 × 52·5	900	900	1952	4 × 320	925	925	1952
	1950		1 × 52·5	900	900	1953	2 × 320	925	925	1953
	1951		1 × 52·5	900	900	1954	2 × 320	925	925	1954
	1952		†1 × 52·5	900	900	1955	2 × 320	925	925	1954
Deptford East H.P.	1946	London Power Co.					2 × 225	950	925	1949
	1951		1 × 52·5	900	900	1953	3 × 250	950	925	1953
	1951		1 × 52·5	900	900	1954	1 × 250	950	925	1954
Fulham	1950	Fulham Borough Council	1 × 60	900	900	1951	—	—	—	—
Hackney 'B' ..	1951	Hackney Borough Council	1 × 30	600	850	1954	1 × 300	625	875	1954
	1952		1 × 30	600	850	1955	1 × 300	625	875	1955
	1952		1 × 30	600	850	‡	1 × 300	625	875	‡
West Ham 'B' ..	1946	West Ham Borough Council	1 × 30	625	860	1949	1 × 180	640	875	1949
	1946						1 × 180	640	875	1950
	1947		1 × 30	625	860	1950	2 × 180	640	875	1950
	1950		1 × 30	625	860	1952	2 × 180	640	875	1952
	1952		1 × 30	625	860	1952	1 × 180	640	875	1952
	1952						1 × 180	640	875	1953
Woolwich H.P. ..	1951	Woolwich Borough Council	1 × 30	600	850	1952	2 × 180	640	865	1952

* Barking 'C' subsequently changed to 540 klb/h.
† Brunswick Wharf subsequently changed to 60 MW installed.
‡ Not yet in commission.

At vesting date, the outstanding 'directions' issued by the Central Electricity Board for the installation of new plant in London covered a period of six years, as shown in Table 4.

This programme called for the building of six new stations, five of which were to be accommodated on existing, or extensions of existing, sites. The sixth station, Brunswick Wharf, was to occupy an entirely new site which was formerly used as a dock by the Port of London Authority.

New sections were to be added to three stations, namely Battersea, Deptford East and Woolwich; and a 60 MW set was to be installed in place of a disused house set at Fulham.

Thus, on vesting date, the London Division had to take over the formidable construction programme of installing 1 162·5 MW of new plant, and steps were taken to combine in one working organization the staff concerned with the various independent projects. Approximately 700 MW of the new plant was being designed by consultants, whilst the remainder was directly designed by the Division.

The experienced and comprehensive construction unit of the former London Power Company provided the nucleus of the new organization, which, with the additional staff mentioned above, was able to take over the work involved in this programme.

(3.3) Plant Planned since Vesting Date

Since the 1st April, 1948, the construction of all new plant has been directed by the Central Electricity Authority, who augmented the Central Electricity Board's original programme for London with the additional plant shown on Table 5. The London Division has therefore been responsible for the installation of 40 turbo-alternators, with a total capacity of 2 048·5 MW, of which 29 were in service before the end of 1956; and 65 boilers, with a total evaporative capacity of 21 590 klb/h, of which 54 were commissioned in the same period.

The total installed capacity of new plant commissioned annually is shown diagrammatically in Fig. 2, from which it will be noted that a record figure of 360 MW was commissioned in 1952. This represented 25% of the total capacity installed by all Divisions in that year.

Table 5

New Plant Projected by the C.E.A. since 1st April, 1948

Station	Programme year	Sets: Number of sets and capacity	Sets: Pressure	Sets: Temperature	Boilers: Number of boilers and capacity	Boilers: Pressure	Boilers: Temperature	Commissioning year
		MW installed	lb/in² (gauge)	°F	klb/h	lb/in² (gauge)	°F	
Acton Lane 'B'	1952	1 × 30	600	850	2 × 240	625	865	1954
	1955	1 × 30	600	850	1 × 240	625	865	1955
	1957				1 × 240	625	865	1956
	1957	1 × 30	600	850	1 × 240	625	865	1957
	1958	2 × 30	600	850	2 × 240	625	865	—
Battersea 'B'	1952	1 × 100	1 350	950				1953
	1952				1 × 425	1 420	965	1954
	1952				2 × 425	1 420	965	1955
Belvedere	1957	1 × 60	900	900	1 × 550	950	925	—
	1958	1 × 60	900	900	1 × 550	950	925	—
	1959	2 × 60	900	900	2 × 550	950	925	—
	1960	1 × 120	1 500	1 000/1 000	1 × 860	1 600	1 010/1 005	—
	1961	1 × 120	1 500	1 000/1 000	1 × 860	1 600	1 010/1 005	—
Brunswick Wharf ..	1956	1 × 60	900	900	1 × 320	925	925	1956
Deptford East H.P. ..	1957				1 × 250	950	925	1956
	1957	1 × 52·5	900	900				—
Woolwich H.P.	1956	1 × 30	600	850	1 × 180	640	865	1955
	1956				1 × 180	640	865	1956

(3.4) Some Features of New Plant

Battersea generating station was finally completed in 1955, and the building is generally as envisaged by Sir Leonard Pearce[5] when the construction was commenced in 1929. It is unlikely that the arrangement of sandwiching the boiler plant between two parallel turbine rooms will ever be repeated, owing to the operating and maintenance limitations which result from this arrangement.

Battersea 'B' turbine room now contains two 100 MW sets and one 60 MW set, operating at 1 350 lb/in² (gauge) and 950° F, and two 1·35 MW back-pressure geared turbo-generators, with associated equipment for supplying heat to the L.C.C. Pimlico Housing Estate and to Dolphin Square.[6] This plant went into commercial operation in January, 1951.

The new Bankside station was planned by the former City of London Company, which had acquired additions to the original station site for this purpose. Sir Leonard Pearce was entrusted with the design of the new station, and this responsibility passed, in due course, to the London Division. The boilers, which were the first major installation of this kind in the country, were designed to burn bunker-grade fuel oil, having a viscosity of 6 500 Redwood No. 1 secs. at 100° F. Oil is delivered to an island jetty by self-propelled, self-discharging oil tankers, and piped through a tunnel beneath the station to underground storage tanks. To facilitate handling, the oil requires to be maintained at approximately 120° F, and an auxiliary low-pressure steam system was installed for this purpose. A supply from this system also provides the heat and hot-water services to the adjacent offices of the Authority at Bankside House. Apart from the oil-burning features and the flue-gas washing plant, referred to in more detail in Section 7, the station is conventional in design and arrangement, the absence of coal and ash-handling equipment facilitating a very neat and clean layout.

Brunswick Wharf Station was planned by the Poplar Borough Council, and is situated in what was originally the East India Export Dock. This site was acquired from the Port of London

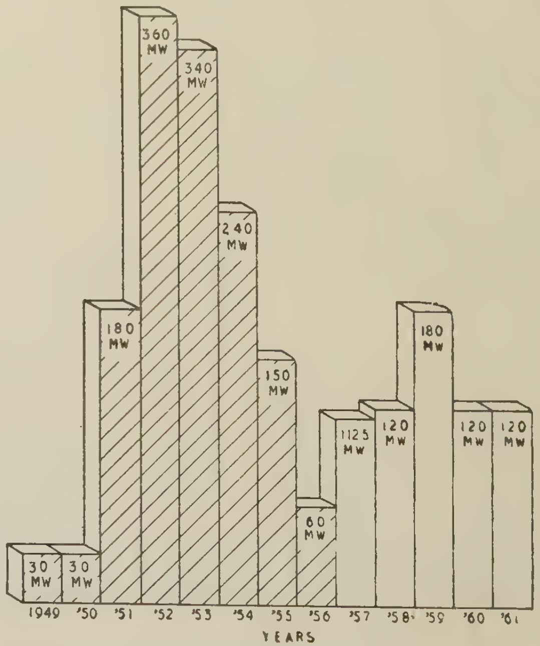

Fig. 2.—Total installed capacity of new and projected plant.

Authority on the condition that the purchaser would provide the impounding water for the remaining East India Import Dock. The old pumping plant which performed this service for both docks is still in service, but has been taken over by the Division. In addition, a 42 in connection is being run from the circulating-water inlet main to the sets, in order to provide a supplementary supply of impounding water from the station circulating-water pumps.

The station was originally planned for six 52·5 MW turbo-generators and twelve 320 klb/h pulverized-fuel-fired boilers. It was subsequently decided, in the interests of capital economy, to increase the capacity of the last two machines to be installed to 60 MW and to eliminate one of the boilers. The operating conditions at the turbine stop valve are 900 lb/in^2 (gauge) and 900° F, and the average thermal efficiency over the 12 months of 1956 was 28·7%, based on the number of kilowatt-hours supplied.

Blackwall Point station, situated on the South Bank of the Thames about half a mile downstream from Brunswick Wharf, is a good example of the efficient use of a restricted site, the total area being only 3·47 acres. The station was completed by 1952, with three 300 klb/h pulverized-fuel-fired boilers and three 30 MW sets receiving steam at 600 lb/in^2 (gauge) and 850° F. The station, except for short periods, has operated on a two-shift basis, and under these conditions has maintained the high thermal efficiency of 26·31% based on the number of kilowatt-hours supplied.

Barking 'C', the third station on the Barking site, was designed for three 75 MW turbo-generators, operating under steam conditions of 900 lb/in^2 (gauge) and 925° F, thus repeating the somewhat unusual set ratings which had been adopted with the lower steam conditions in the Barking 'B' station. It was originally intended to install six 405 klb/h pulverized-fuel-fired boilers, but in order to gain experience of new developments, the fifth boiler was designed to operate with the combustion chamber under pressure, and the sixth boiler was changed completely to a cyclone-fired unit having a capacity of 540 klb/h.

The fifth boiler (No. 43) was constructed with a pressure-tight casing, designed to withstand 27 in (water gauge) static pressure. The casing was fitted as near to the boiler tubes as possible, in order to minimize differential movement, and all unavoidable breaks in the envelope were sealed by expansion joints. Special arrangements had to be made to safeguard the operators and prevent the emission of gas into the boiler house. Soot blowers and lighting-up oil burners, which are normally withdrawn when not in use, required special treatment. Inspection doors and ash-discharging arrangements had to be redesigned, and a system of interlocks was provided to prevent hazardous operation and to avoid dangerous blows of gas from the furnace.

Isolation of the pulverized-fuel mills, when not in service, called for special measures. Provision was made for the mills to be vented in order to release internal pressure, and for the fuel pipes to the burners from isolated mills to be purged continuously, to prevent dust and hot gas from entering the idle fuel burners.

The trunking to and from the induced-draught fans was so arranged that the fans could be by-passed. Suitable interlocked dampers were provided, remotely controlled from the boiler panel. The boiler can be changed from suction to pressure firing in a few minutes. The advantages of pressure firing are reduction in power consumption for auxiliaries, reduced maintenance on induced-draught fans, close control of combustion air and operation at a higher carbon-dioxide value.

The cyclone boiler (No. 44), which has a designed output of 540 klb/h of steam at 950 lb/in^2 (gauge) and 940° F, has three horizontal cyclone furnaces at the front and near the base of the unit. The boiler is designed for pressure firing, similar to boiler 43, and although most of the ash fuses and flows in a molten state from the cyclone furnaces into the secondary furnace and thence to the ash sluice through quenching tanks, electrostatic dust precipitators have been provided to remove residual dust from the waste gases. Once the boiler has been proved, it is planned to experiment with as wide a range of British coal as possible, and to establish whether this type of firing can, with advantage, be used for larger boilers planned for future generating stations.

The above stations, together with the completed station at West Ham and those under construction at Acton Lane and Deptford East, are designed with bus-connected steam and feed-water systems, all boilers supplying steam to, and being fed from, common ranges. In most instances, the boiler capacity installed exceeds the turbine requirements, so that reserve boiler plant is available.

The Hackney 'B' station, where the third 30 MW set is under construction, is the first example of a unit system in the Division, although an emergency cross steam and feed connection is provided. The Hackney station, supplied with cooling water from the River Lea, and discharging into the Hackney Cut, is provided with unit circulating-water pumps, and the cooling system is arranged without condenser, pump or section isolating valves.

To prevent an excessive rise of temperature in the Cut, when the flow of the River Lea is restricted, a mechanically induced draught cooling tower of $2·25 \times 10^6$ gal/h capacity is installed in parallel with the normal system. This is the only tower of this type installed in a British generating station. The conditions at Hackney are somewhat unusual, as the tower is only required to run during very hot, dry periods when the flow of the river is abnormally low. The additional cost of fan power is therefore small compared with the saving in capital charges resulting from the adoption of a mechanical draught tower.

The new station under construction at Belvedere will comprise four 60 MW turbo-generators, operating at 900 lb/in^2 (gauge) and two 120 MW units operating at 1 500 lb/in^2 (gauge), 1 000° F reheated to 1 000° F. Originally designed as a coal-burning station, but later modified for dual firing, the station is now designed to burn initially two grades of oil—conventional heavy fuel oil and a low-flash-point oil containing a high proportion of gasolene. Problems associated with the handling, storing and burning of the latter oil led to special design features and safety measures.

Two other stations, Brunswick Wharf and Barking 'C', are in the process of conversion to burn heavy fuel oil. The arrangement of the plant will make it possible to revert to coal firing at relatively short notice.

(4) OPERATING TECHNIQUES AND EXPERIENCES

(4.1) Plant Availability

The generating-station engineer has a twofold aim in maintaining high availability. The first is to generate as much electricity as possible on the new, high-efficiency plant in the interests of economy; and the second is to ensure that all plant of every type is in service during the winter months of December, January and February, in order to safeguard continuity of supply. By careful planning, and close control, of all maintenance and overhaul work, and by the adoption of new and improved methods, the London Division have been successful in effecting a progressive improvement in plant availability. Fig. 3 shows the average plant availability in the month of January during the period 1949–56, and the substantial reduction in plant outage will be noted. In the last two years of the above period, the outage in January was almost entirely due to major repair work which involved the return of turbo-generator parts to the manufacturers' works.

Fig. 4 shows the reduction in fuel consumption per kilowatt-hour sent out which has been effected since 1948 by improved efficiency of operation.

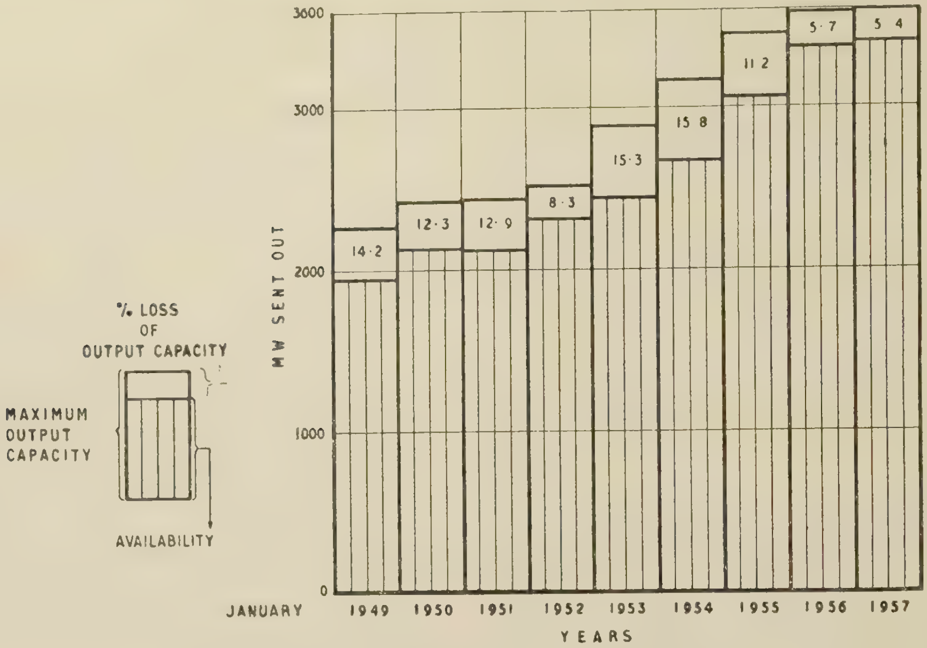

Fig. 3.—Maximum output capacity and plant availability.

(4.2) Boilers

With the exception of the ten 150 klb/h boilers commissioned at Barking 'A' in 1928–30, there were no major pulverized-fuel-fired boilers installed in London prior to the commissioning of the post-war plant. In recent years, the change-over to pulverized-fuel firing has been significant, although it has not been so pronounced in London as in the rest of the country. Since 1948, 27 pulverized-fuel-fired boilers have been brought into service in the London Division, ranging in capacity from 300 to 425 klb/h. These boilers are all provided with electrostatic precipitators.

In order to maintain constant high efficiency of dust removal, the precipitator controls are being brought to the boiler operating panels, and efforts are being made to design an instrument which will give either intermittent or continuous indication of the efficiency of dust collection.

The pulverized-fuel boilers are all direct fired from two or more pulverizing mills, and experience has shown the necessity for close control of the mills, primary air fans and fuel/air supply to the burners, in order to minimize the risk of explosion. Such explosions as have occurred in the London stations followed no uniform pattern, and appeared to be capricious and unpredictable. Based on this experience, a code of practice was adopted which laid down requirements for the effective isolation of mill lines, and gave guidance on the safe operation and control of the equipment. Explosions have rarely, if ever, occurred under stable conditions, but usually when mill lines have been brought in, or taken off, load; or when the rate of firing has been increased, or decreased, rapidly.

The block-faced water-cooled furnace has given way to the completely bare tube furnace in pulverized-fuel boilers. In consequence, liberal use of the lighting-up burners has been found necessary, in order to maintain efficient combustion under starting and light-loading conditions, even when high-volatile coal is available. This has led to the use of oil burners of increased size and capacity, so that, in addition to lighting up, it is possible to bring the boiler on load without using coal.

With the increase in boiler size and the introduction of remote control from the boiler panel, the proper observation of combustion conditions in the furnace has become more important than ever. To provide this facility, use has been made of closed-circuit television, in conjunction with a periscopic arrangement of lenses which is capable of insertion in suitable apertures at the bottom or top of the combustion chamber.

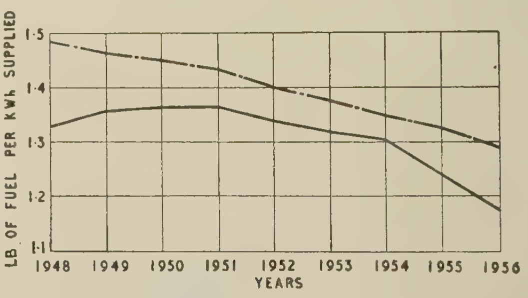

Fig. 4.—Fuel consumption per kilowatt-hour supplied.
— — — England and Wales.
——— London Division.

Of the chain-grate stoker-fired boilers commissioned since vesting date, the four La Mont boilers installed in the Woolwich generating station are worthy of note. They are of 180 klb/h capacity and supply steam at 640 lb/in^2 (gauge) and 865° F. Each unit is provided with one motor-driven and one steam-driven circulating pump. Two of these boilers have been in service for over four years and have maintained a high availability. It is interesting to note that a 220 klb/h La Mont boiler was installed at Deptford West in 1939, and that three 150 klb/h boilers of this type, supplying steam at 1 400 lb/in^2 (gauge) and 960° F, have been in operation at Taylors Lane generating station since 1943–44.

(4.3) Turbines

The Division's principal operating problem has been caused by the advent of the 275 kV Grid and the progressive curtailment

of its base load generation in favour of stations situated nearer the coalfields, where fuel costs are lower.

The safe operation of plant on a two-shift basis requires precise knowledge of turbine operating conditions. In order to provide the operators with information on turbine-shaft displacement and eccentricity in older sets, caused by changes in temperature and loading, it has been found necessary to fit supervisory equipment to the larger sets operating mainly at or above 900 lb/in^2 (gauge) and 900° F. One of the sets being modified is the 105 MW (No. 3) set at Battersea, operating at 600 lb/in^2 (gauge), 850° F. This is a 3-cylinder tandem machine which, although commissioned in July, 1935, is still, at the time of writing, the largest set in operation in Great Britain. By July, 1956, it had generated 11 500 million kWh—a remarkable record for 21 years of base-load operation—giving a load factor of about 60%.

Supervisory equipment has also been fitted to other large units which have for many years operated under base-load conditions.

A large number of tests on various sizes and makes of turbo-generators and associated boilers have been made under carefully controlled conditions, making extensive use of additional instruments. Metal temperatures in various parts of the turbines have been recorded with the aid of thermocouples, and means have been provided for measuring vibration, eccentricity, differential expansion and movements of the parts of the machine. The tests have been carried out with the machine in a 'hot' state after overnight shut-down of from six to eight hours; in a 'warm' state after longer periods of shut-down; and also with the turbine completely 'cold' after a prolonged shut-down. The first of these tests was given special consideration, as the 'hot' state is the condition which occurs most frequently in normal practice.

A quick-starting procedure has been established, which, with minor variations for individual sets, can be applied generally after overnight shut-down. It has been found beneficial to off-load and shut-down the sets as rapidly as possible, in order to minimize the cooling of the metal which results from prolonged periods of light loading. Measures have also been taken to maintain the boilers at as high a temperature as possible during the off-load period. When starting a turbine in the 'hot' state, i.e. after a six- to eight-hour shut-down, particular care is taken to ensure that the steam reaches the turbine at a temperature higher than the metal temperature, and preferably with a margin[7] of 100–150° F.

With 'hot' conditions at the start, 60 MW 3 000 r.p.m. sets have been brought up to full load in less than 30 min from initial admission of steam, without causing any apparent abnormal thermal stresses. A similar rapid increase in steam output from the boiler has also been obtained without loss of operational control, and without subjecting the superheater tube metal to excessive temperatures.

In the London area quick starting has enabled the generating stations to bring plant into service every morning to meet a rate of rise of load which approaches 2 000 MW per hour. Special arrangements are necessary on Monday mornings because plant which has been shut down over the week-end requires a longer period for bringing up to full load. No difficulty, however, is anticipated as more and more plant in London is put on two-shift operation, although in the winter over 3 500 MW of plant will have to be shut down every night and brought into service by 8 a.m. each day.

(4.4) Alternators

The effect of standardization of alternator design since 1948 is seen by comparing the typical machines listed in Tables 6 and 7. It will be seen that the short-circuit ratio is now tending to range

Table 6

TYPICAL PRE-NATIONALIZATION GENERATORS

Station	Rating		Short-circuit ratio	Stator voltage	Generator busbar voltage
	MW	Power factor		kV	kV
Acton Lane 'A' ..	30	0·8	0·445	22	22
Battersea 'A' ..	100	0·9	0·818	11	66
Deptford West ..	35	0·8	1·095	6·6	22
Fulham	60	0·9	0·872	11	66
Woolwich ..	30	0·8	0·65	22	22

Table 7

TYPICAL POST-VESTING-DATE GENERATORS

Station	Rating		Short-circuit ratio	Stator voltage	Generator busbar voltage
	MW	Power factor		kV	kV
Acton Lane 'B' ..	30	0·9	0·84	11·6	22
Bankside 'B' ..	60	0·875	0·7	15	132
Brunswick Wharf	52·5	0·85	0·63	11·8	132
	60	0·8	0·615	11·8	132
Deptford East ..	52·5	0·9	0·72	11·8	66
Belvedere* ..	120	0·9	0·75	13·8	132

* Not yet commissioned.

Table 8

EFFECT OF CABLE-CHARGING MVAR AT TIMES OF LIGHT LOAD

Date	14th April, 1952 0600 hours	28th December, 1953 0300 hours	1st August, 1954 0600 hours
Generation, MW	271	384	343
Generation, MVAr	−42	−41	−55·5
Generation power factor (leading)	0·99	0·99	0·99
Export from London Area, MW	28	49	86
Export from London Area, MVAr	−7	+7	+63
Net London Area load, MW	243	335	257
Net London Area load, MVAr, including charging MVAr of cable system	−35	−48	−118·5
London Area power factor (leading)	0·99	0·99	0·91
Cable-charging MVAr at time of test	−345	−427	−481
MVAr absorbed by frequency changer and shunt reactor	15	30	42·5
London Area MVAr, including magnetizing of transformers and excluding cable charging MVAr	295	349	320
London Area power factor (lagging), including magnetizing of transformers	0·64	0·69	0·63
Total charging MVAr of circuits in commission at time of test	−387	−481	−517
Percentage average system voltage above nominal 66 kV	5·0	4·5	3·7
Percentage maximum system voltage above nominal 66 kV	7·6	9·1	7·7

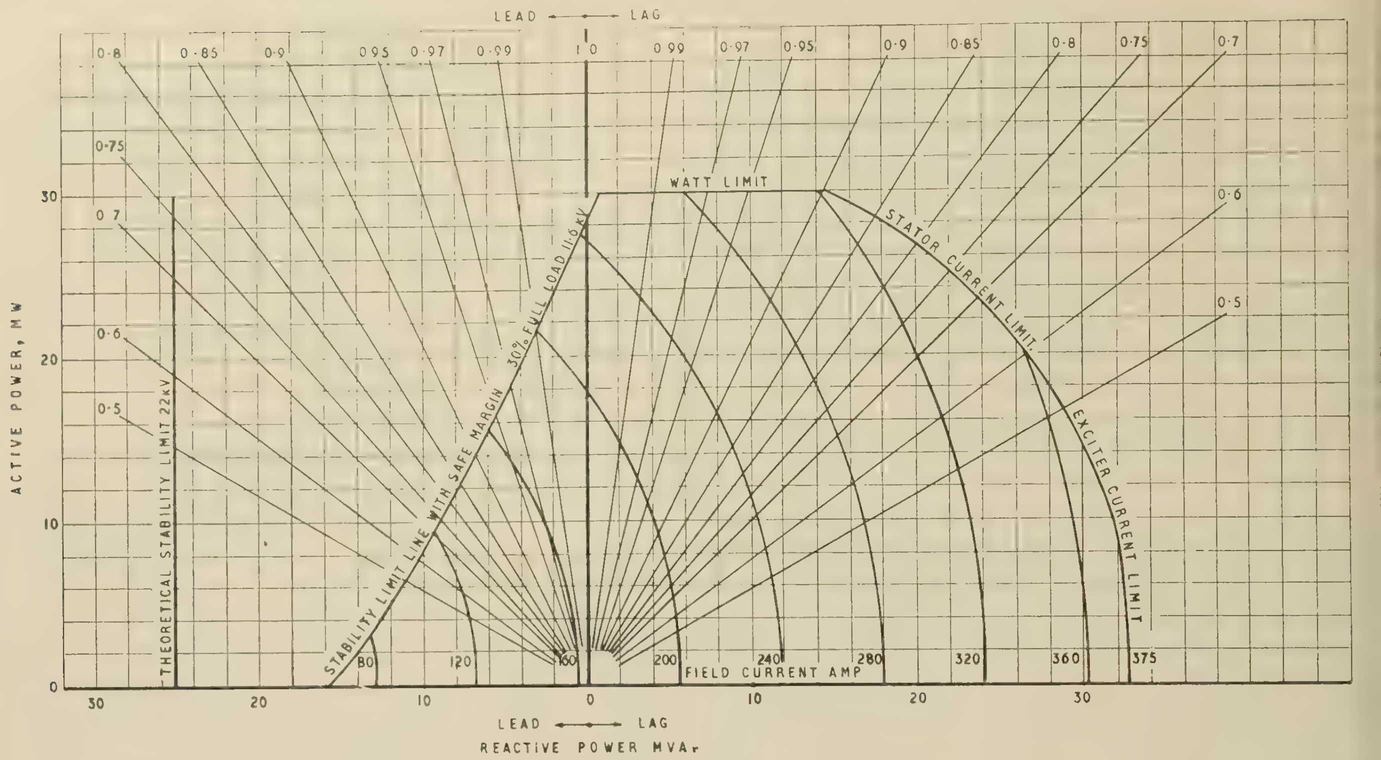

Fig. 5.—Alternator stability diagram.

between the two figures of 0·55 and 0·8, which has been accepted as the most suitable for machines designed for 0·8–0·9 power factor. Also, the stator terminal voltage, for machines connected to step-up transformers, has been left for the turbine manufacturer to decide, instead of the customers themselves, which was quite a common, though unsatisfactory, practice in pre-war days.

Formerly the short-circuit ratios for certain machines in London were specifically chosen to enable them to operate at leading power factors without risk of instability. This operating condition still applies, owing to the exceptionally high charging reactive power required by the extensive cable system in London.

In 1948 some 400 MVAr were required to charge the 22–132 kV cable systems. By 1954 this had increased to 570 MVAr, and it is estimated that by 1960 it will have reached 700 MVAr. Its effect on the system voltage at times of very light load is shown in Table 8.

This heavy charging reactive power has been counteracted to some extent on certain of the longer feeders by installing shunt reactors at one end of sufficient capacity to compensate for half the charging current. Further easement has been provided by two 15 MVA shunt reactors which were connected to the system in 1942, and by a 33 MVA synchronous-motor-driven frequency-changer (installed at Deptford West for supplying the 25 c/s British Railways supply at Deptford East) which can be run as a synchronous condenser. It will be seen from Table 8, however, that, even after all these methods have been adopted, it is still necessary to provide further compensation by running certain generating plant at leading power factors, in order to keep the system voltage under control.

In order to ensure that instability of the generating plant does not occur, stability diagrams of the type shown in Fig. 5 are provided for each machine that has to be run under these conditions.

(5) FUEL SUPPLIES

The River Thames plays a very important part in the supply of fuel to the London Division stations. At vesting date, a total of 18 colliers were taken over by the London Division from the London Power Company (the first electricity undertaking in the country to own colliers) and the Fulham Borough Council. Several new ships were ordered by the C.E.A., following a decision taken shortly after nationalization that the number of vessels owned by the Authority should be capable of carrying at least 60% of the total seaborne coal required, leaving 40% to be carried in chartered vessels. In the national interest, it was considered advisable to continue the use of some chartered ships as a contribution towards the maintenance of the vigorous service of coastal shipping which is so vital to the country in times of emergency. The upriver colliers—colloquially known as 'flat-irons'—are of particular interest, since they have been specially designed to negotiate the low arches of the ten road bridges and five railway bridges which cross the Thames between the Pool and Fulham. In 1956 no fewer than 38 colliers were employed regularly in supplying fuel to the London Division, their carrying capacities ranging from 1 500 to 4 500 tons. Of these, 27 were owned by the C.E.A.

The fuel supplies to the London Division for the calendar year 1956 are shown in Table 9, and are classified in accordance with the method of transport used. In referring to this Table, it must be understood that the expression 'ship direct' is applied to coal which is railborne from the pit to the port of loading, and then shipped direct to the station. The quantity of imported coal is of particular interest. It should be noted that this figure is not typical of the country as a whole, and is exceptionally high on account of London's particular dependence on seaborne deliveries. During recent months the tonnage of imported coal has fallen considerably, and at the end of 1956 it represented only

5% of the total supplies, whereas during the previous winter it was as high as 25%.

A stocking ground, with a capacity of 300 000 tons, is rented near Dagenham Dock, in order to supplement the stocks held at stations with limited storage facilities, and also to provide a working reserve to cover emergencies resulting from bad weather, labour difficulties and similar causes.

The current consumption of fuel by the London stations is nearly 7 million tons per annum. By arrangement with the National Coal Board it has been possible to reduce the variety of coal delivered to any one station, thus stabilizing the quality. Even with the poorer grades of coal, stabilization can have beneficial results. Transport and handling costs have been reduced by ensuring that seaborne coal is drawn from the pits nearest to the port of loading, and railborne coal is drawn from the pits nearest to London.

It will be seen from Table 9 that approximately 63 000 tons of coal were carried in road vehicles direct from the pits to the stations. This refers to coal from the East Midlands area, and represents an effort to reduce transport costs on coal normally carried by rail.

Table 9

FUEL SUPPLIES TO LONDON DIVISION C.E.A. FOR THE YEAR ENDED 31ST DECEMBER, 1956

Nearly 7 million tons of fuel were delivered to London generating stations. An analysis of this figure, showing the methods of transport employed, is given below:

	tons	Percentage of total
To Stations		
British coal ex N.C.B.		
Ship direct	4 787 502	68·84
Rail direct	544 163	7·82
Road direct	62 688	0·90
Ship and barge	245 302	3·52
Rail and barge	153 417	2·20
Rail and road	9 513	0·13
Ship and rail	560	0·08
Ship, barge and road	18 547	0·26
Foreign coal imported		
Ship direct	593 657	8·53
Ship and barge	61 990	0·89
Ship and road	11 682	0·16
To Dagenham		
British coal by ship direct	137 897	1·98
Foreign coal by ship direct	54 039	0·77
Total coal	6 680 957	96·08
Total coke breeze	154 760	2·23
Total oil	108 755	1·56
Total coal-tar fuel	9 134	0·13
	6 953 606	100·00
Coal withdrawn from Dagenham		
Ship	18 384	
Rail	9 138	
Barge	160 695	
Road	10 146	
Barge and road	3 690	
	202 053	

The coke consumed in the Division takes the form of coke breeze, and it is extensively burnt, with considerable success, at West Ham 'B' and the Deptford stations. The breeze is mixed with coal in the handling process, and at West Ham 'B' the high proportion of 45% coke breeze to 55% coal has been achieved.

Most of the oil is consumed at Bankside 'B', which is the first British generating station to be designed to burn oil exclusively in large, modern, boilers. Oil is also burnt at Islington, where a 120 klb/h boiler was installed in 1928. It is believed that this was the largest oil-fired unit in the country at that date. The future use of oil for supplementing available coal supplies has received much consideration recently; and arrangements are in hand to convert Brunswick Wharf and Barking 'C' generating stations (with the exception of the cyclone boiler at the latter) to oil firing. The new station being constructed at Belvedere will, in the first instance, burn fuel oil only. The total consumption of oil at the two stations being converted will be some 600 000 tons per annum by 1958–59. The Belvedere station will require some 590 000 tons per annum when completed.

Fig. 6 shows the works cost per kilowatt-hour sent out and the delivered cost of fuel for each year since nationalization.

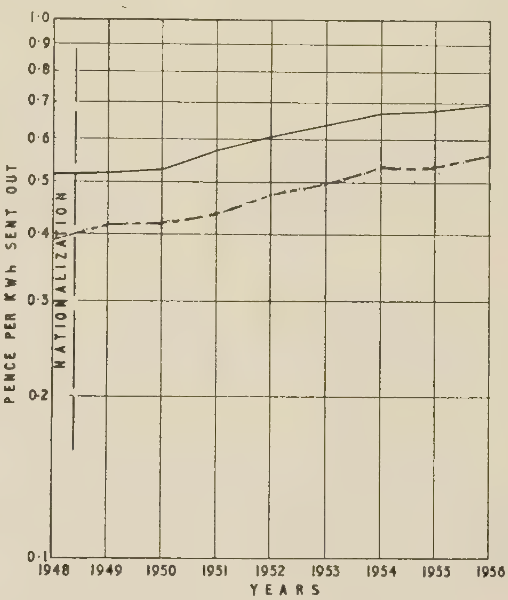

Fig. 6.—Relationship between total works costs and the cost of fuel delivered.

——— Total works cost.
— — — Delivered cost of fuel.

It will be seen that the increasing cost is mainly due to the rising pithead prices and that works costs have risen less quickly. This is due to improvements in maintenance, availability and operating techniques partially offsetting rising labour costs. It must be remembered that large quantities of foreign coal were imported in 1955 and the early part of 1956, and this tended to reduce the overall transport costs in the London Division. It should also be noted that the pattern of supplies has essentially changed, and this obscures many differences in costs. For example, in the early years following nationalization, large quantities of coal from north-east England were replaced by supplies from the East Midlands coalfields. This had the effect of reducing the pithead price of coal delivered to London, as the East Midlands coal was cheaper; but it also substantially increased the transport costs.

(6) ASH

With the increasing adoption of pulverized-fuel firing, the handling and disposal of the resulting fine ash has required special attention.

Ash from the boiler combustion chamber is normally removed

wet, being quenched by sprays as it falls into the ash hopper. The bare-tube construction, which is used in all modern water-cooled combustion chambers, does not encourage the formation of clinker, and the resulting ash consists almost entirely of granular particles, or dust. Before the ash can be transported in bulk by road, it requires to be de-watered, and this draining process presents some difficulties.

The pulverized-fuel ash from the precipitators is removed to storage hoppers, and is normally conditioned for road transport by wetting. Intensive investigations have been carried out, with a view to finding uses for pulverized-fuel ash; and these researches have proved it to be a satisfactory ingredient for brick making and for a variety of concrete and mortar mixtures. Arrangements have therefore been made at some stations for the ash to be supplied in bulk in suitably designed vehicles, for commercial purposes. At Hackney generating station a bag-filling machine has been installed, in order that dry ash may be offered for sale in standard self-sealing paper bags of the type normally used for cement.

A great deal of experimental work has also been done on the sintering of the ash, in order to convert it into a light-weight aggregate for building purposes. The Division has granted facilities for a British company to construct a full-scale plant at Battersea generating station to exploit the process devised by Dr. F. P. Somogyi. This plant is capable of producing 300 tons of sintered ash per day. The dust is delivered dry to the sintering plant, where it is nodulized into pellets of approximately $\frac{1}{2}$ in diameter, which are then delivered to the top of a vertical kiln. The temperature for sintering is automatically controlled at a point below the melting point of the ash, no fuel being necessary to maintain combustion, which is entirely sustained by the residual carbon in the ash. This is thought to be possible with ash having as low a carbon content as 4%. The sintered product is continuously discharged from the bottom of the kiln and then passes through crushers before being finally graded for use. This type of aggregate has been found to be very suitable for use in light concrete structures, and for replacing clinker in the manufacture of building blocks.

(7) AVOIDANCE OF ATMOSPHERIC POLLUTION

One of the important recommendations made by the Committee set up by the former Electricity Commissioners in 1930 to investigate emission from generating-station chimneys was that chimneys should be at least $2\frac{1}{2}$ times the height of the main station building,[8] in order to be remote from the effect of down-draught. This recommendation was generally accepted by undertakings, and stations built after about 1935 were provided with tall chimneys.

Many of the older stations in London have numerous short stacks, each boiler usually being provided with a separate chimney. In London, 70% of the generating-station chimneys are less than 200 ft in total height above ground level, but in 1955–56 the plant connected to those chimneys generated only 4% of the total energy sent out by the London stations. It is significant that 80% of the total output was sent out from stations with chimneys 275 ft, and over, in height.

The new stations at Acton Lane, Bankside and Hackney, apart from having tall chimneys, also have nozzles provided at the exit which have the effect of accelerating the discharge of the gases and adding to the effective height of the chimneys. The effect is particularly noticeable under light or moderate wind conditions.

The Division co-operates with the D.S.I.R. and local authorities in maintaining a large number of gauges for measuring deposition and sulphur from the atmosphere, and nearly half of the 300 instruments in London are maintained by the London Division. The long-term objective of these investigations is to determine, first, the degree of pollution which is normal to particular districts; and secondly to detect any increase which may be attributed to generating-station emission, in order that immediate investigations can be made and remedial measures undertaken, if necessary.

Grit emission from the low chimneys of the older boilers is controlled by using selected high-grade fuel and by steaming the boilers below their rated capacities, to enable optimum combustion conditions to be obtained. All new boiler plant installed during the period under review is equipped with high-efficiency mechanical dust-arresting plant, or electrostatic precipitators, resulting in an emission to the atmosphere as low as $0\cdot1$ grain/ft^3. This compares very favourably with the generally accepted figure at the beginning of the period under review, which was $0\cdot4$ grain/ft^3.

Battersea and Bankside generating stations are both equipped with flue-gas washing plants for the removal of sulphur dioxide.[9]

The original Battersea plant, taken out of commission during the war years, at the Government's request, was reinstated between the years 1949 and 1951, involving major reconstruction work. The gas-washing towers, or absorption chambers, are in the base of the stacks, and the fourth tower and stack was completed during the commissioning of the final extension in 1955. The plant has been considerably redesigned and is being successfully maintained at a standard never before attempted. The greatest problem is still the provision of materials of construction which will not rapidly deteriorate and yet are not prohibitive in price. There are now four double-flow absorption chambers, one under each of the four chimneys, and the design of the water-spray system, scrubbers and chamber lining must be such, together with the lasting properties of the materials used, that complete overhaul and reconstruction will only be necessary every fourth year. When the modifications are completed, it should be possible to rehabilitate one chimney and absorption chamber in three or four weeks. At present this work requires an outage period of at least six months.

At Battersea, the sulphur content of the fuel fired is limited to about 1%, or less, by burning selected coals, and it is thus possible to maintain the efficiency of sulphur removal at 85–90%, but this is achieved at an all-in cost of about 10s. per ton of coal burnt.

The Bankside flue-gas washing plant was designed after experiments had been carried out on a pilot scale. Although similar in principle to the Battersea plant, it embodies many improvements and modifications, being designed to deal with the gases produced by burning oil with a sulphur content of up to 4%. Up to the present, this plant has consistently maintained an efficiency of sulphur dioxide removal of over 95%.

(8) DEVELOPMENT OF THE TRANSMISSION SYSTEM

(8.1) General

Since vesting date, extension of the transmission system has been necessary, owing to three main causes:

(a) Provision of new points of supply to the London Area Board.
(b) Provision of outlets from new generating plant.
(c) Provision of 50 c/s supplies to British Railways (Southern Region).

Most of the additional transmission has been provided by underground cable, the exception being the Brunswick Wharf–Brimsdown 132 kV overhead line which traverses the industrial East End of London.

The difficulty of constructing this line can be gauged from the fact that, of the 74 towers used in its $12\cdot6$-mile length, only

Table 10

LENGTHS AND TYPES OF CABLE OWNED BY THE LONDON DIVISION AT THE 1ST APRIL, 1948 AND 1957

System voltage	Circuit-miles, 1st April, 1948				Circuit-miles, 1st April, 1957			
	Solid type	Oil-filled	Gas pressure	Total	Solid type	Oil-filled	Gas pressure	Total
132 kV	—	39·93	1·00	40·93	—	56·25	31·69	87·94
66 kV	110·82	62·94	5·20	178·96	111·64	71·04	29·87	212·55
33 kV	23·93	4·20	—	28·13	17·92	9·30	—	27·22
Below 33 kV	66·61	—	—	66·61	61·07	—	0·32	61·39
Total for all voltages ..	201·36	107·07	6·20	314·63	190·63	136·59	61·88	389·10

seven are of the straight-line type, and all but two are fitted with extensions. The line was one of the first in the country to be strung with the $0{\cdot}4\,in^2$ copper equivalent s.c.a. conductor rated at 146 MVA per circuit, and the conductors were fully grease-impregnated against corrosion. Details of cables in commission at vesting date and at the 1st April, 1957, are given in Table 10. Nearly 100 circuit-miles of high-voltage cable have been laid, and the Table indicates the general trend of progress in design. The pressure of the gas pressure cables is $200\,lb/in^2$ (nominal).

The changes shown at 33 kV and below are mainly due to transfers of ownership to and from the London Area Board following change of use. The inclusion of 0·32 mile of gas-pressure cable below 33 kV is of interest and refers to the cables laid at Woolwich generating station between two 45 MVA 132/22 kV transformers and the power-station switchgear. In normal circumstances, it would be expected that such short lengths of cable at this voltage would be of the solid type, but owing to the rating required and the difficulties of routing, advantage was taken of the higher conductor temperature of 85° C permissible with oil-filled and gas-filled cables, as compared with 65° C for solid cables in similar situations.

It is interesting to refer in passing to the continual increase in cable length between joints. It was common practice in 1948 to install 220 yd lengths of cable, but it is now possible, where conditions are favourable, for $\frac{1}{2}$-mile lengths of 132 kV single-core cable to be laid, and in fact over 600 yd lengths of this type of cable have been installed in heavily congested areas adjacent to Finsbury Market substation.

(8.2) Transmission Voltages

The early cable interconnection system in London was at 66 kV. Later, certain sections were installed operating at 132 kV. The occasions when 66 kV is justified are now rare, and extension of the system at 132 kV is normal.

At present, the 275 kV Grid circuits are being brought to within some 20 miles of London at Elstree, West Weybridge, Iver and Tilbury. At a later date, a supply point will also be provided at Northfleet.

Owing to the advantages of riverside power stations, the amount of electricity generated within the London Division has, in the past, greatly exceeded local consumption, and the Division has therefore exported to surrounding areas, to the extent shown in Table 11.

This will remain true in the future at times of peak load, but owing to coal transport costs, the trend will be to supply London's base load from the cheap-coal stations in the Midlands via the 275 kV Grid.

Table 11

	Kilowatt-hours sent out from London Division	Kilowatt-hours taken by L.E.B.	Divisional maximum demand sent out	L.E.B. simultaneous maximum demand
	kWh × 10^3	kWh × 10^3	kW	kW
1948–49	8 764 657	5 182 610		Not charged on simultaneous maximum demand basis
1949–50	8 781 032	5 367 738		
1950–51	9 537 795	5 091 574*		
1951–52	9 521 426	5 205 271	2 253 000	1 409 014
1952–53	9 565 986	5 443 874	2 276 000	1 512 596
1953–54	9 914 923	5 646 971	2 701 000	1 715 571
1954–55	11 194 632	6 181 939	3 028 000	1 746 004
1955–56	12 352 539	6 628 376	3 113 000	1 933 079
			These figures are not necessarily coincidental with L.E.B. maximum demand	

* Reduction due to Southern Electricity Board load at Acton Lane being transferred from L.E.B. sale to Divisional sale.

(8.3) Switchgear and Short-Circuit Levels

The short-circuit rating of 132 kV gear installed in 1949 was increased to 2 500 MVA, and all new equipment commissioned since 1952 has had a breaking capacity of 3 500 MVA. The 66 kV switchgear has been uprated in a large number of cases and now ranges between 1 500 and 2 500 MVA, the latter figure being necessary when infeeds from the 275 kV Grid points via the 66 kV cable systems have to be met. Two interesting examples of 132 kV air-blast switchgear installed indoors are to be seen at Brunswick Wharf and Barking, having breaking capacities of 2 500 and 3 500 MVA, respectively.

The short-circuit levels of much of the lower-breaking-capacity gear in the generating stations have had to be reduced, either by installing reactors or by suitable switching of circuits, in order to meet the Area Board requirements.

The lower-voltage switchgear to which Area Board circuits

are connected is therefore operating in the main with the following short-circuit levels:

33 kV	750 MVA
22 kV	500 MVA
11–6·6 kV	250–150 MVA

The limitation of breaking capacity has been effected either by connecting large external reactors in series with the transformers or generators feeding the busbars from which the Area Board take their supply, or by installing transformers designed to have very high internal impedance.

When extending existing systems it is economically preferable to install reactors, but for new sites, or when the voltage is being increased from 6·6 to 11 kV on old sites, the transformers are designed with high internal impedance, the voltage being kept under control by providing an adequate range of taps.

Owing to the national short-circuit problem, the C.E.A. has found it necessary to specify the following transformer reactance figures:

Voltage	*Transformer size*	*Reactance*
kV	MVA	%
132/11	30	20
132/33	30	10
132/33	45 and 60	12½
132/33	75	15
132/33	90 and over	17

Tapping range +10% −20%

These values are also applicable to the 66 kV system in London, but it has been found that they are still too low in certain cases. In one instance, two 30 MVA 66/11 kV transformers supplying a load of some 40 MVA had to be designed for 24% internal reactance.

(9) RESEARCH AND INVESTIGATION

Pure fundamental research is outside the scope of a Generation Division, but a valuable contribution to applied research has been made by the London Division's engineers and chemists, both independently and in collaboration with the C.E.A. Research Department. In the compass of the paper it is impossible to do more than indicate the type of investigations which have been undertaken.

Mention has already been made in Section 4.3 of the investigations into turbine quick-starting techniques which have been carried out at Brunswick Wharf and Bankside 'B', and similar investigations at other stations are projected.

Reference has also been made to the development of the gas-washing plant for the oil-fired boilers at Bankside, in Section 7. London can claim to have been associated with all the pioneer work connected with the extraction of sulphur from flue gases. Prior to the last war, the only two gas-washing plants in the country were installed at Battersea and Fulham. The Battersea plant was an effluent system discharging into the River Thames; as mentioned in Section 7, it is in operation, in a developed and extended form, at present. The Fulham plant was a non-effluent system and was not reinstated after being taken out of commission, at the request of the Government, during the war years.

A team of engineers drawn from the Division, the C.E.A. and the C.E.A. Research Laboratories at Leatherhead, are carrying out extensive research into the characteristics of flame radiation on one of the boilers at Brunswick Wharf generating station. To determine the primary and secondary air quantities, special nozzles were designed and tested with the aid of a quarter-scale model of the duct-work. In order to measure the temperature of the gases leaving the combustion chamber, suction pyrometers had to be specially developed, since no suitable instruments were available for this purpose. A special ash sampler had also to be constructed for use at this position. Initial tests have been carried out to determine the heat absorption under different conditions of burner angle and excess air and coincident measurements of wall-tube fin temperature have also been taken, together with radiation and optical pyrometer readings.

Tests have also been carried out at Taylors Lane generating station, in conjunction with the C.E.A. and the appropriate manufacturers, to determine the magnitude of the metal temperature gradient within a steam pipe and flange when bringing a boiler on load; and also to ascertain the accuracy of steam-temperature measurements in the 900–1 000° F range.

In an attempt to improve condenser efficiency by preventing the formation of a water film over the tubes, various types of 'dropwise condensation promoters'—such as lauryl mercaptan—have been tested at Deptford East generating station.

Extended experiments in the burning of coal with high chlorine content have been conducted at Acton Lane generating station where boilers are installed with radiant superheaters.

Research into the feasibility of extracting germanium from fly ash has been carried out by the Chemistry Section of the Division.

Considerable use has been made of ultrasonic and magnetic methods for detecting caustic and other cracking in boiler drums.

The Division has its own hydraulics laboratory, and undertakes Venturi calibrations for a number of outside bodies. The Laboratory has a capacity of over one million gallons per hour and is one of the largest in the country.

Whilst the above random examples cannot give a truly balanced picture of the research carried out in the Division, it is hoped that they will at least indicate the versatility of the work undertaken.

(10) ADMINISTRATION

At vesting date the need for co-ordination and the application of uniform methods of administration was at once apparent. On the other hand, there was widespread and ample evidence of devoted and loyal service by the staff in the true tradition of the industry, who did their best, under difficult conditions, to maintain the service at a high level of operating efficiency.

To many of the former undertakings, the generating station was the main centre of the individual organization, and the transfer of control produced a few problems, some of which arose out of the determination of the boundaries of responsibility between the Area Electricity Boards and the Division. Most of the stations were the main distribution centres of the former undertakings, and in some instances the remnants of d.c. systems were supplied from converting machinery housed in the station.

The defining and allocation of assets between the Board and the Division, the take-over and purchase of stores, the payment of salaries and wages, the co-ordination of fuel supplies and the disposal of ash, had all to be dealt with by the new organization in addition to providing technical support and direction for the station engineers in meeting extremely heavy demands practically throughout the year, caused by the generating plant shortage of that period.

Many of the old stations made, and continue to make, a vital contribution to meet the public demand.

The Generation Divisions are management units of the Authority's organization for generation and bulk transmission. The Divisional Controller manages his Division in conformity with the Authority's technical, financial and administrative policies, and within the framework of the Authority's arrangements for national co-ordination. These arrangements are far-

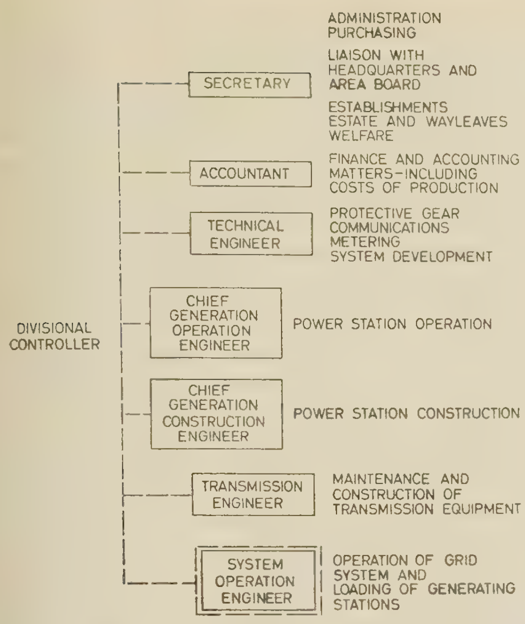

Fig. 7.—Organization of London Division.

reaching, and necessitate close co-operation between each Controller and the Authority's staff at their national headquarters.

Fig. 7 shows diagrammatically the organization of the London Division.

The scope of Divisional management varies according to the need for national planning and co-ordination within each function. In some cases a great deal has to be done at the centre, from technical necessity or because of the Authority's statutory obligations; in other cases, the extent of Divisional responsibility is a matter of administrative expediency for decision by the Authority.

The scope of Divisional management in matters of administration is very wide. With regard to staff and organization, the Authority is concerned only in the general outline of organization, the most senior appointments and the total number of staff employed. Legal issues and those involved in the management of lands and buildings are the subject of consultation with the legal advisers and estates officers at the Authority's headquarters. Insurance and superannuation are dealt with within the framework of national agreements applying to the industry as a whole.

In the London Division, financial control and policy generally are dealt with by means of a Management Committee consisting of the seven chief departmental officers with the Controller as chairman. This Committee has, in turn, set up an Establishment Sub-committee to consider personnel matters, again with the Controller as chairman.

In matters of finance, the Controller has been delegated powers from the C.E.A. to expend sums not exceeding £5 000 in respect of any one project. For contracts between £5 000 and £100 000 the C.E.A. has delegated powers of acceptance to a Divisional Panel consisting of certain members of the Management Committee. Contracts exceeding £100 000 are recommended for acceptance to the Chief Engineer of the C.E.A.

Management within the Division is based on the conception of each generating station being an industrial unit with management responsibility delegated to the station superintendent, including control of stores, wages and costing.

The Construction Department, in addition to supervising work carried out by consulting engineers, have, since 1948, successfully designed and engineered some major projects; the new stations at Hackney and Acton Lane are examples, and only at the former were civil-engineering consultants employed. In addition, the completion of Battersea and Woolwich and the rebuilding of Deptford East stations were not only engineered entirely by the Division, but most of the building and civil-engineering work has been done by direct labour employed by the Division.

(11) ACKNOWLEDGMENTS

The author wishes to express his thanks to the members of the staff of the London Division who assisted him in the preparation of the paper.

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[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE INSTITUTION, 24TH APRIL, 1958

Sir John Hacking: It is an honour, as well as a pleasure to open the discussion on the paper. It is a pleasure because I played some small part in setting up the various Divisions which were entrusted with the work of constructing and operating the generating plant in the London area, and it is always pleasant to follow work of that sort and to admire it when it is done well, as it has been in this case.

The author describes the work of the London Generating Division, which is one of the 14 Divisions with similar functions set up as a result of the 1947 Act. Measured in terms of capacity of generating plant it was, in 1948, the largest of these Divisions, whilst measured in terms of territory it was the smallest.

I propose to describe quite briefly some of the salient points in the history of the electricity supply industry, prior to the 1947 Act, for indeed the industry had quite a long and chequered history before 1947.

The conversion of mechanical energy into electrical energy was made possible by the discovery of the principles of electromagnetic induction by Michael Faraday in 1831, and it is appropriate that his portrait should find an honoured place on the walls of the Lecture Theatre. The reverse conversion to produce mechanical energy from electrical energy also led, of course, to the development of electric motors and the large industrial developments which have followed.

Generators are of little use unless their output can be put to some useful purpose. Their first use was for supply to arc lamps in lighthouses, Humphry Davy having demonstrated in 1808 that brilliant light could be produced by passing current from batteries between two contra points. It is worthy of note that both Davy's discovery of arc lighting and Faraday's discovery of the principles of electromagnetic induction were made and demonstrated to the public at the Royal Institution in London.

The first public supplies of electricity in England were started in 1878, in which year several public installations using arc lamps were carried out in London.

The rapid spread of the use of electric lighting was, however, due to the development of incandescent lighting. Joseph Swan had been experimenting with carbon-filament lamps as early as 1860, but his first simple form of lamp does not appear to have been demonstrated until February, 1879. In the meantime, Edison in the United States had been experimenting with filaments of different rare metals. In October, 1878, he announced that he had achieved success with carbon filaments. The similar discoveries of these two pioneers, working independently over 3 000 miles apart, led to both providing installations in London, but fortunately the two combined and acute controversy was avoided.

There were wide differences of opinion about the type of supply which should be given. The main point of difference was whether an a.c. or d.c. system should be used. There seems to have been a very strong preference for d.c. supplies, largely, I think, because of the availability of batteries, which could be used not only to safeguard supplies but also to improve the load factor on the plant which was provided.

The a.c. supplies were single phase; 3-phase supplies were not provided until much later. Sebastian de Ferranti was one of the protagonists of the a.c. system. He had been manufacturing single-phase generating plant at the age of 21, when he became the Chief Engineer of the London Electricity Supply Corporation in 1886. Until then all the engineers had thought in terms of small stations to supply relatively small areas, but Ferranti was strongly of the opinion that generation should be done on as large a scale and as economically as possible. It was not essential for the generating plant to be near the load, he said, because it was practicable and economical to transmit electricity over quite appreciable distances to supply the local load.

He therefore selected a site on the River Thames at Deptford for development. He planned a station with a capacity of 120 000 h.p. in units of 10 000 h.p. each, which was far in excess of anything that had been built before. Two of those units were, in fact, ordered. The only motive power available was from reciprocating engines, and some of the literature describes the enormous engines which were projected.

For the second part of his major scheme, i.e. the question of transmission, he conceived the idea of a cable system at 10 kV single-phase. As there was no manufacturer available to construct that type of cable, he arranged to do it himself.

There was difficulty at that time—in fact, there has always been difficulty between the companies and the local authorities—about wayleaves for cables, and in order to avoid that, he made arrangements with various railway companies to run this 10 kV cable along their rights of way.

The scheme was a major conception. The difficulties in its way were obviously greater than Ferranti foresaw. There were considerable delays in the construction of the Deptford station, and the situation was aggravated by a bad fire in the power station at Grosvenor Gallery which was supplying the load. As a result, the company decided to abandon the rather big plan for Deptford. They re-erected in Deptford some of the sets from the Grosvenor Gallery station and supplemented them with smaller sets.

It was still necessary to go ahead with the cable scheme, and this was still in commission not so many years ago. This was a twin concentric cable manufactured by Ferranti and built under his direction. It gave service over a period which is comparable with that provided by the present-day cables.

Ferranti's connection with the Company came to an end in 1891, and thereafter he went back to his old love and established a successful manufacturing concern. There is no doubt that although his efforts in this instance seem to have been a failure, his ideas were sound and have been followed by supply engineers all over the world.

I have already mentioned that the first generating units were driven by reciprocating engines. The first turbo-generator in the world was built by Charles Parsons in 1884, and it well merits the place which it now occupies in the Science Museum at South Kensington. It was a d.c. machine. The first turbines to be installed in generating stations were apparently in the Forth Bank station of the Newcastle and District Company; two of these were installed in 1890, each with a capacity of 75 kW. These were single-phase machines operating at 1 kV 80 c/s.

The extension of the use of turbines was slow, but others were installed at Cambridge and other plants. It certainly would not have been possible to develop generating units of the size described in the paper had it not been for Charles Parsons's invention of the turbine. Perhaps somebody else would have invented it, but nevertheless it is clear that it must have saved a great deal of time and been of great assistance to power supply engineers. Not only do we have 105 MW units—the largest in commission in this country—but there are units of 275 MW, and even one of 550 MW projected, and some of those of 120 MW must be approaching completion.

So far as I know, the first system to give 3-phase supplies in this country was supplied from Neptune Bank station on Tyneside, where Charles Merz started his work for electricity supply. This station and system were developed with the main idea of

supplying power for the shipyards. It was rather a difficult application with which to start, but it was a huge success. From a fear whether they could afford to pay the price for the electricity, the shipbuilders ended by using several times as much power as they had before, not because the power itself was cheap but because it enabled them to get very much better output.

At Neptune Bank, too, there were installed in 1901 Parsons 3-phase turbines of 1·5 MW, and these were followed in 1904 by the installation in the new Carville station of turbo-generator sets of 3 000 h.p. There is a classic description of the Carville power station in a paper presented to The Institution in 1904 by Charles Merz and William McLellan.

The early advances of the industry were undoubtedly much delayed by difficulties between the companies, who wanted to give supplies in particular areas, and the local authorities, who wanted to reserve to themselves the right to give those supplies although very often they were not prepared to go ahead at the time. The situation became so bad that, after considerable discussion, an Act was passed in 1882 which tried to regulate the position and to provide for power-supply companies obtaining statutory powers in local-authority areas. The President of the Board of Trade at the time was Mr. Joseph Chamberlain, who had had extensive municipal experience and had been Mayor of Birmingham, and perhaps it is not surprising that the Act, when it was passed, was very favourable to the local authorities and therefore relatively unfavourable to the companies. Amongst other things, it included a provision that, at the end of 20 years, the whole installation should be handed over to the local authorities at cost, without any allowance for goodwill or future prospects.

There was not much development following that Act, but in 1888 a modifying Act was passed which extended the period from 21 to 42 years and considerably increased the facilities. As a result, a large number of power schemes went ahead. A big scheme was prepared for London in 1905 which involved the provision of a very large generating station at Barking with supplies to a very large part of London. That Bill went through both Houses until it reached the third reading, when it was lost because the Government was thrown out. The L.C.C. were the principal of very many opponents to this scheme, but a few years afterwards they came forward with a Bill on almost the same lines. That, in turn, did not go through because of the intervention of the 1914–18 War.

During this war the increasing importance of adequate electricity supplies was emphasized, and in 1919 an Act was passed which created better co-ordination of supplies. It provided for dividing the country into larger areas of supply and for the establishment of a series of joint electricity undertakings. It was hoped that there might be agreement between the various supply undertakings about supply in each of those areas, but there were no compulsory powers for ensuring this. It was dependent entirely on voluntary arrangement between the companies and the local authorities, and this was not forthcoming on the scale desired. As a result, only five joint electricity undertakings were set up covering much less than one-fifth of the country, while the remainder continued as before.

This state of affairs continued until the Electricity Act of 1926. This provided for the setting up of the Central Electricity Board with responsibilities over the whole country. One of the major duties, which is sometimes overlooked, was the standardization of frequency throughout the country. Before that there had been some standardization over fairly wide areas, but whilst the greater part of the country used 50 c/s, there were large and important areas with 40 c/s and 25 c/s supplies. The cost of standardizing the frequency to 50 c/s was upwards of £7 million, and when one realizes that the capacities of all electricity supply systems have been doubling roughly every 10 years, and are therefore now more than 8 times what they were in 1926, it will be appreciated how expensive standardization of frequency would be if it had to be undertaken at the present time.

The Central Electricity Board did not own any generating stations, with the exception of one which was erected during the war. However, it had powers to select generating stations to be operated in accordance with its directions, although there was no change in ownership of the stations. The Central Electricity Board also had the duty of providing a transmission Grid to interconnect the selected stations of the country and to give supplies to other areas. This enabled concentration of generation on the more efficient areas as well as a substantial pooling of capacity with consequent economies in the total capacity of plant required.

The transmission system created by the Central Electricity Board provided a measure of interconnection between generating stations over the whole of Great Britain, with the exception of the North of Scotland area.

The 1926 Act did not deal with distribution, which was left in the hands of municipalities and companies who had the necessary statutory powers. It was not until the 1947 Act that distribution was centralized in the hands of 14 Area Boards, whilst ownership of generating plant was vested in the one body, the British Electricity Authority

Mr. W. N. Kilner: The paper is of great interest in showing many factors which must be considered in order to obtain maximum availability and maximum operating efficiency from power-station plant. It does not state, however, why the fuel consumption per kWh is so much lower in the London Division than in England and Wales as a whole. The author implies in Section 4 that the improved fuel efficiency in the London Division since 1948 is due to improved operational efficiency, but is it not partly due to the installation of new and more efficient plant? From Fig. 4, it may be significant that, up to 1951, new generating plant installed in the London Division since vesting day was only 2·3% of the installed capacity, whereas this figure had risen to 32% by 1955 and to 34% by 1956. These figures are also typical of the average for the country as a whole, and considerable manufacturing effort was required to achieve them.

According to the published figures for the year 1956, over half the total output from the London Division was produced by plant installed after 1945, and some 13 sets, none more than four years old, were responsible for nearly one-third of the total output. Another factor which would affect the fuel consumption referred to in Fig. 4 is the quality of the coal used. Was better-quality coal used in the later years in which the fuel consumption was lower?

Mr. L. H. Welch: Fig. 7 indicates that the secretarial staff of the Division are in liaison with the London Electricity Board. Although not shown in this Figure, there is very close liaison between the Division and the Board on the engineering side, too, and it is this co-operation that has helped to produce many of the good results.

The Division and Board are interdependent to a large degree. Last year 70% of the Board's total income went to the Division; it was only 60% in 1948, and I hope this shows that we, too, have improved. Both are represented on all the joint negotiating and advisory machinery. If there are schemes for education and training in one of the organizations, there are sure to be similar schemes in the other, and here again I would like to pay tribute to the author and the Division for the close-co-operation that has been achieved in this sphere.

The maximum demand of the London Electricity Board occurs

about 5 p.m., and this should give the Division a chance to export more power at the time of the national peak, which is about 8.30 a.m., but I regret that the Board still provides 75% of the Division's income for 60% of the output from the Division, and I have never been able to understand that!

When I view the London Division, as their chief customer, I view it from three angles—How reliable is the supply, what is its quality, and how much does it cost? I have the fullest possible praise for the reliability, and I think that the London Division have a record which is to be envied anywhere in the country, as there have been no major shut-downs since vesting day. The voltage stability is reasonable, although there have been occasional troubles. The frequency stability is good, except at times of load shedding, and were it not for the rest of the country, ample supplies would be available for London. The cost per kWh has increased by 50% since 1948, but it is pleasing to record that the Board, by their efforts, have only had to increase their price to consumers by 16%.

The Board are always reproached for not having a better load factor. Whilst there is no space to do justice to a discussion on such a weighty matter, it is not just a question of telling the Board to lower its prices at night or off-peak times. Any improvement can only be achieved as a result of a combined operation for the whole industry, and unless the C.E.G.B. lowers the prices at off-peak times, there is little chance of the Board achieving anything by this particular method.

Mr. E. B. Powell: The restriction of short-circuit levels by an extensive use of high-reactance equipment on the 11 and 6·6 kV busbars has to be accepted when the loads are highly concentrated. This free use of reactance, whether incorporated in the transformer design or connected externally, is looked upon by many engineers with extreme disfavour. In London, however, the whole transmission system is very compact, and the increase in phase angle between the various sections of the system due to the presence of reactances does not amount to more than 5° to 8°. This can be ignored from the point of view of system stability. The power factor of the load is also high, which reduces the voltage drop. There is no doubt, therefore, that by the liberal use of reactors the output capacity of individual supply points has been kept up, with a resultant reduction in both transmission losses and capital charges.

The charging of the large transmission system supplied by the London Division, which will probably reach 800 MVAr by 1960, tends to cause high voltages at times of light load. This is kept under control by running the 33 MVA 50/25 c/s frequency-changer at Deptford as a synchronous condenser. This machine was originally installed in 1932 in order to enable the efficient 50 c/s plant at Deptford West to help supply the 25 c/s railway load at Deptford East. It is interesting that, owing to the small amount of plant interconnected at this time, the greater part of the railway load fluctuations were transferred to the older station at Acton Lane, which had turbines with very sensitive governors. The economy expected was therefore not obtained. The machine has, however, proved to be invaluable for voltage control. It assisted the Central Electricity Board in the early 1930's when they were having bad insulator flashover troubles.

In 1945 the machine was again used to absorb all the swings on the railway 25 c/s load, when all the fluctuations were taken by the very large interconnected Grid system. It was therefore considered that the help given to the Central Electricity Board in the early 1930's reaped a justifiable reward at a later date.

Mr. W. N. C. Clinch: The paper is interesting, but in some cases it is ungenerous. The author tells us about the marvellous means whereby they have adopted quick-starting methods, but he has dealt only with the means and not the method.

In Section 7 there is a reference to the Battersea plant. I agree that the author has made one think that the white Whitsun gloves of purity can be worn if clean coal is used.

Why are we changing some of our boilers to oil-firing when a Committee is sitting to inquire into how the country can use the small coal, of which there is a surplus at present? It seems that there must be a lack of balance somewhere.

The author might have paid a little more tribute to the honourable intentions of those who were in the electricity supply industry before 1948. They did their best to maintain the electricity supply in England and part of Scotland so that it was not affected by the efforts of Parliament, which passes Acts but never has to put them into effect.

In Fig. 7 there is reference to a technical engineer. I know that the C.E.G.B. will have to have a technical engineer, but in this case it is the technical electrical engineer which is meant. Technical engineers are complete bodies of engineers; they are technical. But the man in question is electrical.

Mr. C. C. Barnes (*communicated*): Table 10 is particularly interesting. At 66 and 132 kV the large increase of gas-pressure cable installations is very noticeable. For important cable installations it is C.E.G.B. practice to obtain competitive tenders and the final assessment of these offers depends on two important criteria—technical adequacy for the service conditions obtaining and economic assessment.

The C.E.G.B. base their technical requirements on successful compliance with type tests, which are short-time proving tests made on a miniature cable system incorporating cable, straight-through and trifurcating joints and terminations. These type tests are summarized below.

(*a*) *Loading-cycle test.*—Twenty heat cycles of six hours heating, of which the latter half must be approximately constant at the maximum conductor temperature plus 5° C (i.e. 85° C + 5° C for 33–132 kV pressure systems), followed by 18 hours cooling. The voltage must be maintained continuously at 1·5 times the working voltage.

(*b*) *Hot impulse voltage test.*—The test assembly at the minimum design gas or oil pressure must be submitted to and withstand ten successive negative, followed by ten successive positive impulses (without arcing horns) at the following voltages:

Service voltage kV	*Impulse voltage* kV(peak)
33	194
66	342
132	640

The impulse wave must have a wavefront between 0·5 and 5 microsec and a time to half value of 50 microsec, other appropriate requirements being as given in B.S. 923. The heating current (85° C) is maintained continuously during the whole of the testing period.

(*c*) The following tests are also carried out: Cold power-factor/voltage, dielectric thermal resistance, mechanical test on the metallic reinforcement, and a saline bath test on the anti-corrosion coverings. A range of sample tests are also made.

The above type tests are complementary to the earlier long-term design tests made by the cable makers as part of their own development programme. When interested manufacturers have successfully passed the type tests, a careful economic assessment of their tenders is made in order to decide on the cable system to be used.

As a major experiment the first 3-core 132 kV gas-filled cable was commissioned by the Central Electricity Board at Burford, Oxfordshire, in May, 1944. The first commercial installation of 3-core mass-impregnated gas-filled cable, designed for a

maximum electrical stress of 100 kV/cm (minimum radial thickness of insulation, 0·41 in) and approximately five miles in length from Barking to Ilford, has now completed over five years' successful service experience.

WESTERN CENTRE, AT CARDIFF, 10TH FEBRUARY, 1958

Mr. R. S. Atkinson: The paper is a factual survey of what has been and is being done to meet the electrical energy requirements of London, and is therefore not of a highly controversial or provocative nature. It is, in fact, a record of the problems of congestion and concentration arising from the high density of population and building in the London area.

An example is the difficulty encountered in selecting a route for the Brunswick Wharf–Brimsdown 132 kV line, on which the author points out that, of 74 towers, only seven are of the straight-line type and all but two are fitted with extensions. This inevitably raises the question of what the pattern of electricity generation in London will be in the future with roads, bridges, tunnels and railways already congested with electrical and other competing services and with riverside and urban sites for generating stations almost non-existent. Will the future lie in the encirclement of the London area by the high-voltage transmission system with radial infeeds?

I am pleased to see a particular reference to the Battersea No. 3 105 MW set installed in 1935 and to its excellent production record. This is a fine tribute to the wisdom and foresight of the engineers responsible at that time.

The reference to Barking No. 44 boiler with its cyclone furnace is of special interest because of the experiments being carried out there with a wide range of fuels. It has long been realized that the Welsh-coalfield low-voltatile fuels cannot be burnt satisfactorily in a pulverized-fuel furnace using normally commercially attainable fineness of grinding without suffering an excessively high carbon loss in the ash produced. Possibly a cyclone furnace could provide a solution to this problem, provided that a satisfactory means of maintaining fluidity of the ash were achieved.

Fig. 2 indicates the widely changing load factor under which the construction engineers in the London Division have had to work, varying from 360 MW in 1952, down to 60 MW in 1956 and up again to 180 MW in 1959. This helps to demonstrate the need for the recent decision of the Central Electricity Generating Board to regionalize power-station construction into only three units, so that a steadier work load might be achieved.

Emphasis is currently placed on the need to turn to commercial advantage the waste products of industry, and it is extremely encouraging to learn of the satisfactory progress that has been made in London in the production of light-weight sintered aggregate. As so often happens, this substitute product has real advantages over the original material which it replaces.

My only disappointment is that no reference has been made in the paper to education and training, because I know that a tremendous amount of work has been done in this connection, not only in selecting and training engineers up to the professional standards of The Institution but also in training craftsmen and operators and in teaching new techniques and methods to enable them to keep abreast of current developments.

Mr. W. Wilde: The importance of plant availability, referred to in Section 4.1, is not always fully appreciated. Thermal efficiency, which may be described as a 'standard of operation', has rightly received much attention, but 'availability', which may be described as a standard of maintenance, is of much greater importance. Clearly the amount of 'spare' capital plant which it is necessary to provide depends upon the percentage availability of plant, particularly during the December–March period. The outage of a 60 MW unit of high merit may cost up to £2 000 per day, and at the other end of the scale, if load shedding becomes necessary because of the non-availability of low merit plant, the loss of revenue to the C.E.G.B. and to the Area Board concerned is equal to the load shed times the maximum demand charge.

In Section 4.2 the author refers to the development of pulverized fuel in the London area. The earlier experiences gained at Barking, Stepney, St. Pancras and Taylors Lane were such that there was very strong resistance by local authorities and others to further installations of pulverized-fuel-fired plant in the London area. In the pre-war period the engineers responsible for some of the larger stations in London were unable to install pulverized-fuel firing and had to turn to other developments in the field of combustion engineering, for example the retort-type stoker, but with the satisfactory development of pulverized-fuel firing and particularly the improved performance of electrostatic precipitators, post-war development of pulverized-fuel firing was rapid and over $1\frac{1}{4}$ million kW of pulverized-fuel plant is now in service in the London area.

In Section 4.3 the author refers to quick-starting techniques in the areas remote from the coalfields. The power stations will be operated on a two-shift or peak-load basis and be shut down overnight. The rate of rise of load at these stations in the London area will exceed 2 million kW per hour now, and it is therefore essential that the starting up and loading procedures can be carried out day by day with absolute certainty. Tests which have been carried out to establish these 'quick' or 'safe' starting techniques have shown that there are methods of measurement which go a long way to help in achieving this end. For example, eccentricity of turbine shafts, differential expansion between rotor and cylinder, overall expansion and vibration, the monitoring and control of metal temperatures and steam temperatures, both on boilers and turbines, are of great importance in these techniques.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. H. V. Pugh (*in reply*): Sir John Hacking has provided a concise history of the supply industry prior to 1948, and has dealt, in particular, with the important part played by Sebastian de Ferranti in his early conception of the large central generating station and transmission of electrical power over long distances. There is evidence in Deptford East Power Station to-day of the work attributed to Ferranti, and many of the other older power stations have relics of the pioneering work carried out by engineers in the industry at the turn of the century. It was not possible to deal with this fascinating story in the paper, which, owing to limitations of space, had to be confined to the period 1948–56.

The fuel consumption per kilowatt-hour for the period shown in Fig. 4 is lower in the London Division than in England and Wales as a whole, because, at the commencement of that period, there was a concentration in London of large more modern stations operated at a high load factor under the direction of the Central Electricity Board. As Mr. Kilner points out, only 2·3% of the installed capacity in 1951 was new plant installed since vesting day; many of the older stations were brought back into service for much longer periods of the year than had been the case just prior to 1948. This was necessary between 1948 and 1952 because of generating plant shortage, and it had the effect in London of increasing the overall fuel consumption per kilo-

watt-hour over that period. The consumption would, however, have been much worse but for considerable improvements in operating efficiency; Mr. Kilner is, nevertheless, quite correct in his submission that, subsequent to 1952, the reduction in fuel consumption was largely due to the coming into service of much new higher-efficiency plant. I agree also that, subsequent to 1952, the large amount of plant commissioned was possible only because of the very special efforts of the manufacturers. The improvement in fuel consumption in London was not helped by London stations receiving better-quality fuel; in fact the quality tended to deteriorate, but the new plant, and particularly the pulverized-fuel-fired boilers, was able to use the poorer-quality fuel so well that no measurable loss of efficiency resulted.

I am grateful to Mr. Welch for his confirmation of the co-operation which exists in London between the generating and distributing sides of the supply industry. His statement that the London Electricity Board still provides 75% of the London Division income for 60% of the output from the Division is not correct. Forty per cent of the output is transmitted to other Divisions, which are credited with the income but not debited with the cost, and so it is not possible to produce a true balance sheet for the Division. Table 11 gives the number of kilowatt-hours produced by the London Division and taken by the London Electricity Board, for which, of course, they have paid the Division at the bulk supply tariff.

Mr. Powell has emphasized the two main features in the London power system: the need to restrict short-circuit levels and the control of heavy charging reactive power for the extensive cable system.

Mr. Atkinson refers to an important activity in the Division not mentioned in the paper, in his statement that education and training have over the years been provided in ever-increasing measures, commencing with the essential training of apprentices both as craftsmen and engineers. The Bankside Apprentices Basic Training School, instituted in 1953, has provided over 250 boys with a sound foundation on which the remainder of their apprenticeship has been built.

DISCUSSION ON 'ELECTRIC CONTROL OF STAGE AND TELEVISION LIGHTING'*

Before a joint meeting of the North-Western Utilization Group *and the* North-Western Radio and Telecommunication Group *at Manchester, 11th February,* 1958.

Mr. R. W. Koplick: With the continual increase in the size of new television studios, the lighting control console will tend to become larger and more cumbersome than ever, and some attempt should therefore be made to design a unit which has only a basic number of dimmer control levers and switch tablets, which can be switched to control any section of the studio; for example, the studio may have 400 ways divided into eight areas, so that the control facilities need be capable of handling only 50 ways at any given time. Thus with the aid of presetting switches it would be possible to switch the control facilities on the console from one area of action to another as required; and while it would be feasible only with the so-called 'inertia' system, i.e. the electro-mechanical arrangement of resistance or transformer dimmers, it is one way of overcoming the disadvantage of large consoles which seem to be inevitable in the future.

Mr. C. S. Bayliffe also contributed to the discussion.

Mr. F. Bentham (*in reply*): This question is of great interest. It has no application in the theatre, because there the whole of the same stage is frequently in use at the one time. Where—as in the case of 'My Fair Lady' at Drury Lane—there are 150 dimmer controlled circuits, we need 150 control levers for them at the desk. In television, however, only limited sections of the studio are in camera view at each particular moment, and we are therefore concerned with a limited number of dimmer control levers. Outside that section or scene, dimmers may be in use but static, at any rate at that moment. The circuit composition of each section cannot be fixed; it will vary from production to production.

I agree with Mr. Koplick that the next step in control must be to take advantage of this fact of television production; then the lighting operator (supervisor) could have a small intimate group of dimmer controls—probably not more than 36—which would not only be less confusing for him but would enable him to be better positioned.

The procedure would be as follows:

(*a*) The studio circuits (several hundred) are patched to a lesser number of dimmer channels, all of which will have dimmers, a ratio of circuits to channels of 3 or 4 to 1 being likely.

(*b*) Dimmer channels will be grouped up to a lesser number of control levers (perhaps 3 or 4 to 1) to suit each scene (series of related camera shots). This arrangement to be planned in advance, at the same time as each production lighting layout is devised.

(*c*) At rehearsal, as each camera shot permits, the appropriate scene master-switch is closed and the dimmers are moved to give the effective lighting. A scene memory button then stores that particular lighting plot complete and then the levers are used for the next scene. It is unlikely that the scenes can be lit in exactly their running order, and therefore the machine must take up the information at random and release it in an order imposed later by the operator.

(*d*) At any time it must be possible to modify any lighting effect already stored, and this means that the memory will then be connected to the dimmer levers and these move to the actual positions for the full lighting effect. The operator can then modify his lighting picture in all its interrelated aspects.

This requirement will be even more necessary with colour television, where the change of one colour in one part of the scene may require the complete 'repainting' of the lighting with touches on all the component dimmer levers.

More development must be done before the above can be achieved, and, in particular, a larger sum of money would have to be allocated to the lighting control than at the moment. Such a system tidies up the control, because space at the desk is occupied only by the one scene or part of scene in view and the operator is not confused by the presence of other scenes.

* Bentham, F. P.: Paper No. 2424 U, November, 1957 (see 105 A, p. 128).

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AN EXPERIMENTAL ELECTRONIC POWER-SYSTEM SIMULATOR

By K. G. CORLESS, B.Eng., and A. S. ALDRED, M.Sc., Associate Member.

(*The paper was first received* 17*th October*, 1957, *and in revised form* 18*th March*, 1958.)

SUMMARY

The problem of power-system simulation is approached by considering the system as an integrated physical interconnection of generators, transmission network and load. In this way a freedom of design ensues which would not be possible if the work were identified with the need to render existing network analysers automatic.

A d.c. electronic analogue computer for synchronous-machine representation which invokes the minimum number of assumptions is coupled to a high-frequency impedance analogue for the transmission network, to form a composite system simulator.

To facilitate the study of simulation techniques the power system is reduced to the basic two-machine configuration. This preserves the essential characteristics of a synchronous system and ensures that the techniques will be applicable to a multi-machine simulator.

The paper describes the simulator and concludes with some solutions of representative problems.

LIST OF PRINCIPAL SYMBOLS

δ = Rotor angle.
f = Frequency.
H = Inertia constant.
$M = H/180f$.
P_i = Power input from prime mover.
P_o = Power output of synchronous generator.
P_m = Maximum power output.
$p\Theta$ = Speed.
v_{fd} = Field voltage.
R_{fd} = Field resistance.
i_{fd} = Field current.
X_{fd} = Field reactance.
X_{ad} = Mutual reactance between field and direct-axis armature winding.
$V_{fd} = \dfrac{v_{fd}}{R_{fd}} X_{ad} p\Theta$ = open-circuit excitation voltage.
$V = i_{fd} X_{ad} p\Theta$, a voltage proportional to field current.
ψ_{fd} = Field flux linkage.
$\Psi_{fd} = \psi_{fd}\dfrac{X_{ad}}{X_{fd}}$ = field flux linkage referred to armature.
τ_{d0} = Open-circuit field time-constant $= \dfrac{X_{fd}}{R_{fd}}$
K_d = Damping torque coefficient.
v = Busbar voltage.
θ = Angle between load-current vector and quadrature axis.
$\cos\phi$ = Synchronous-machine terminal power factor.
v_{dm}, v_d = Direct-axis machine terminal voltage and busbar voltage respectively.
v_{qm}, v_q = Quadrature-axis machine terminal voltage and busbar voltage respectively.
i_d, i_q = Direct-axis current and quadrature-axis current respectively.
i = Load current $= \sqrt{(i_d^2 + i_q^2)}$.
R_m, R_l = Machine resistance and transmission-line resistance respectively.
X_{dm}, X_{qm} = Machine direct- and quadrature-axis synchronous reactance respectively.
X_l = Transmission-line series reactance.
X'_{dm} = Machine direct-axis transient reactance.
$V_q = V - i_d(X_{dm} - X_{qm})$.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Corless and Mr. Aldred are in the Department of Electrical Engineering, University of Liverpool.

(1) INTRODUCTION

A laboratory study of the behaviour of an entire electric power system under the variety of operational conditions occurring in practice is a formidable task. It is practically impossible to express mathematically the equations of performance for the complete system, which would normally be desirable as a first analytical step. The introduction of the a.c. network analyser has provided an acceptable analogue for the complex interconnecting networks, but there remain serious difficulties of adequate synchronous-machine representation for transient-stability analysis and steady-state load balancing. Consequently, certain assumptions and approximations concerning the machine have been made, but these must be strictly limited if the resulting solution is to have any practical significance.

The inadequacies of network analysers for system studies have naturally led to the development of analogues for the synchronous machine, and a considerable volume of literature exists on the problem of rendering network analysers automatic.[1, 2, 3, 4, 5, 6] However, the majority of these machine analogues have been developed specifically for use with existing network analysers and many retain the conventional synchronous-machine assumptions.

The authors have adopted a different approach to the problem by reconsidering generators, transmission network and load as an integrated system to be represented by a composite simulator. This permits, for example, the use of high-speed automatic calculators, which allow many of the assumptions and approximations used hitherto to be discarded.

The aim of the work covered by the paper was to develop an experimental model which would simulate automatically the behaviour of a composite power system and invoke the minimum number of approximations, and to analyse the effects of some of those used hitherto. To facilitate the study of simulation techniques, the power system has been reduced to the basic two-machine configuration. This preserves all the essential characteristics of a synchronous system and therefore ensures that the techniques will be applicable to a multi-machine simulator.

(2) THE PROBLEM OF SYSTEM SIMULATION

The problem reduces logically to the adequate representation of machine and transmission network and methods of coupling them. These three aspects of the problem are now considered.

The most accurate description of the behaviour of a synchronous machine is contained in the equations by Park,[7] which express the performance of all types of ideal synchronous machinery under both steady-state and transient conditions.

Field time-constant, synchronous and transient reactances, armature resistance and inertia constant are all represented. Moreover, in Park's reference frame all the variables are unidirectional quantities and therefore the equations are amenable to solution by automatic d.c. calculator.

The choice between digital- and analogue-computer solution of the equations is influenced by the fact that synchronous-machine parameters are often not known with great accuracy. The relative accuracies of the two types of computer are therefore of little consequence, and the facilities of the analogue for continuous solution and readily variable coefficients are a considerable asset. A paper has been published describing a d.c. electronic analogue computer for the solution of Park's equations[1] and this has been adapted for inclusion in the simulator.

The following assumptions have been made concerning the generator:

(*a*) All waveforms are sinusoidal and remain so.
(*b*) The effects of saturation and of eddy-current and hysteresis losses are negligible.
(*c*) During any transient which results in the machine remaining in synchronism, the speed change is a negligible fraction of fundamental speed.
(*d*) Voltages induced in the armature by rate of change of armature flux-linkages are negligible compared with the voltages generated by these fluxes rotating at fundamental speed.
(*e*) The governor of the prime mover is insensitive to the speed changes referred to in (*c*), so that the mechanical input power to the generator can be considered constant.

No terminal-voltage regulator action has been included, although the use of an electronic analogue computer renders it a relatively simple matter for this to be taken into account.

The intricate transmission networks encountered in practical system studies complicate the expression of the electrical transmission equations, particularly if line resistance and shunt capacitance are included. It is therefore not convenient to represent the network by an electronic analogue computer, so that other forms of analogue must be considered. The most commonly used is the a.c. impedance analogue consisting of iterated T- or π-sections. The purpose of other methods of network representation[8, 9, 10] is to conserve the cost of a large-scale analogue, but so far as this work is concerned the network analogue is a small-scale laboratory model and cost is not of prime importance. An a.c. impedance analogue is therefore preferred.

Regarding the operating frequency of the impedance analogue, it should be noted that in stability studies it is the machine that is in the transient state and not the transmission line. The duration of line transient phenomena is a very small fraction of the period of swing of the machine, and therefore for the purpose of machine-stability studies the line can be considered to be in the steady state and be represented by a steady-state analogue. Consequently, the ratio of operating frequency to machine swing-frequency can be quite arbitrary. The choice of base frequency is, however, of importance from other considerations, since the physical sizes of many of the constituent parts of the simulator tend to be reduced as the frequency is raised, although an upper limit is usually placed by the increasing effect of stray capacitance.

The use of an a.c. impedance analogue for the transmission network in conjunction with a d.c. analogue computer for the synchronous machine implies that special coupling units have to be designed to transform the computer-solution voltages into their a.c. equivalents, and vice versa. The units and their functions are as follows:

(*a*) An amplitude modulator which will modulate the amplitude of the a.c. signal supplied to the impedance analogue in conformity with the d.c. computer solution for machine voltage.
(*b*) A phase modulator to modulate the phase of this signal in conformity with the computer solution for machine-rotor phase-angle displacement.
(*c*) Circuits to derive the direct- and quadrature-axis components of a.c. machine load current and provide these as d.c. voltages for the computer.

(3) THE COMPOSITE SIMULATOR

(3.1) The Synchronous-Machine Analogue Computer

Park's equations have been simplified according to the assumptions of Section 2, and then rearranged into a form more suitable for analogue computation as shown in eqns. (1) to (5), where the algebraic signs correspond to a generator. The derivation of these equations is shown in Section 9.1.

For the field we have

$$\Psi_{fd} = \frac{V_{fd} - V}{\tau_{d0}p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$V = \Psi_{fd} + (X_{dm} - X'_{dm})i_d \quad . \quad . \quad . \quad . \quad (2)$$

$$V_q = V - (X_{dm} - X_{qm})i_d \quad . \quad . \quad . \quad . \quad (3)$$

The power output is given by

$$P_0 = V_q i_q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and the equation of motion is

$$M\frac{d^2\delta}{dt^2} = P_i - P_o - K_d\frac{d\delta}{dt} \quad . \quad . \quad . \quad . \quad (5)$$

If Park's equations are set out diagrammatically with the direct and quadrature axes at right angles, as shown in Fig. 1, the

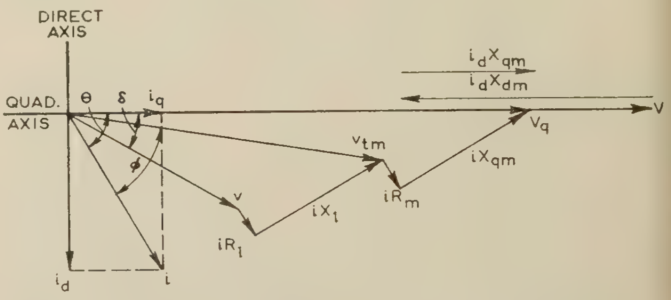

Fig. 1.—Space-time vector diagram for the synchronous machine.

result is a diagram which is identical to the accepted vector diagram of the a.c. machine as developed by Blondel. This is so because the direct- and quadrature-axis voltages and currents of Park are simply the direct- and quadrature-axis components of the peak values of the machine voltages and currents. Therefore, by considering Fig. 1 as lying in the complex plane with the direct and quadrature axes lying along the imaginary and real axes respectively, it is possible to use Park's equations in order to derive an expression for machine terminal voltage in terms of the machine reactances, currents and internal electromotive forces. It is shown in Section 9.2 that by writing the machine terminal voltage as

$$v_{tm} = v_{qm} - jv_{dm} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

substituting for v_{qm} and v_{dm} from Park's equations and writing machine load current as

$$i = i_q - ji_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

eqn. (6) reduces to

$$v_{tm} = V_q - (R_m + jX_{qm})i \quad . \quad . \quad . \quad (8)$$

which is valid for both steady-state and transient operation. The machine terminal voltage can therefore be derived by regarding the machine as a source of alternating voltage V_q with an internal impedance $(R_m + jX_{qm})$. This can be easily represented in the impedance analogue and avoids the need to compute terminal voltage in the electronic analogue.

The interconnection of the computer operational amplifiers for the solution of eqns. (1)–(5), and (8) is shown in the simulator block diagram of Fig. 2. Field time-constant τ_{d0}, synchronous saliency $(X_{dm} - X_{qm})$, transiency $(X_{dm} - X'_{dm})$, inertia constant

Generator load current is monitored by means of a current shunt and a 1 : 1 isolating transformer, as shown in Fig. 2.

Analyser base quantities are:

(*a*) Impedance = 5 000 ohms.
(*b*) Voltage = 10 volts r.m.s.
(*c*) Frequency = 15·915 kc/s ($\omega = 10^5$), established by a crystal oscillator.

Base impedance is equal to the characteristic impedance of the line and therefore unit power of the equivalent system is 2·5 kW/kV².

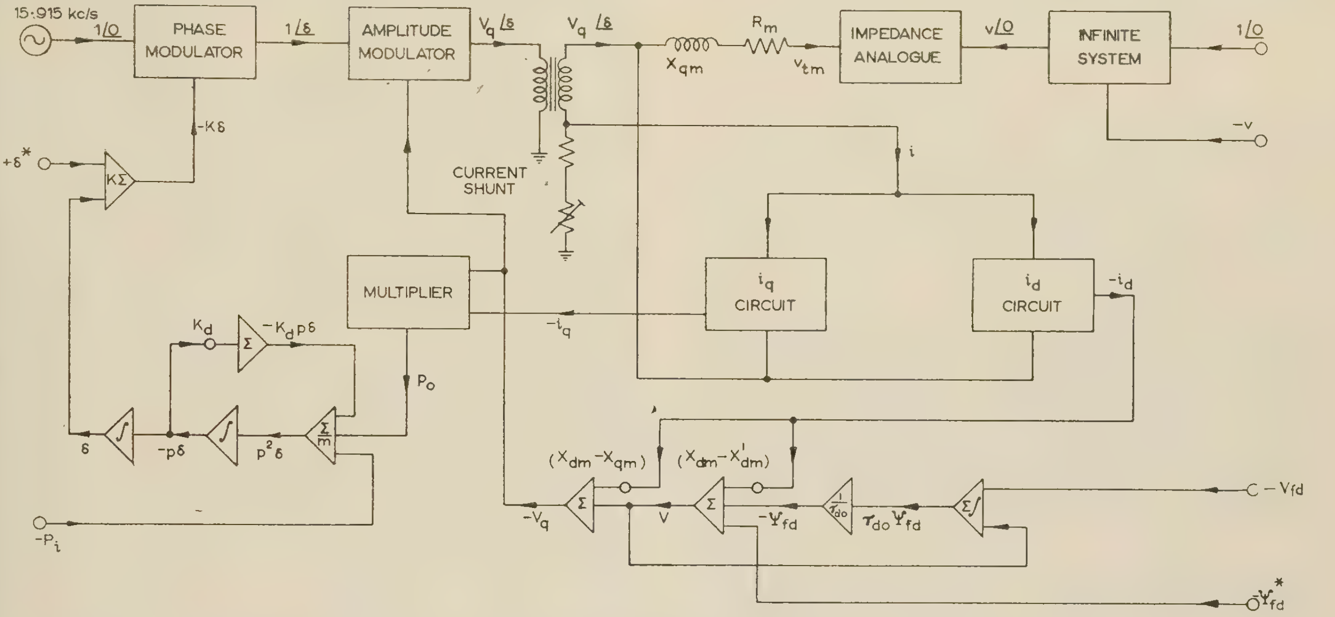

Fig. 2.—Composite simulator.

H, and viscous damping coefficient K_d, all appear as settings of ten-turn helical potentiometers and are readily varied.

Although the computer operational amplifiers are of similar design to those described in Reference 1, minor changes have been made to the computer scale-factors which render the time scale-factor independent of the value of inertia constant. In addition, the multiplier squaring circuits have been redesigned and have segmented diode characteristics,[1] which leads to improved accuracy and stability.

Computation is continuous since line faults can be applied and cleared directly in the transmission-line analogue, and there is therefore no necessity to 'hold' the computer.

(3.2) The A.C. Impedance Analogue

The a.c. impedance analogue operates at a frequency of 15·915 kc/s and is a steady-state, single-phase representation of a 3-phase transmission line. It comprises two parallel circuits, each equivalent to 500 miles of distributed-constant line, and includes shunt capacitance and series resistance. One line is in ten sections, terminated by the contacts of two high-speed relays to represent circuit-breaker action. A balanced 3-phase fault can be applied at any of the ten sections by a third high-speed short-circuiting relay. Unbalanced faults could be represented by using the appropriate negative and zero-sequence networks interposed between the fault busbar and neutral busbar as usual.

Relay operations to simulate fault application, clearing and subsequent reclosing are co-ordinated by the control unit (Section 3.4).

Line inductors are of fixed value and conveniently wound on small Ferroxcube pot cores, having Q-factors of 150–200; the resistances of the line inductors can therefore be safely ignored.

The 1 : 1 isolating transformer is also wound on a Ferroxcube pot core, the primary and secondary windings being bifilar to minimize leakage inductance. Primary and secondary reactances are 3·0 per unit, and the total leakage reactance is about 0·002 per unit.

(3.3) Coupling Units

(3.3.1) The Amplitude Modulator.

A block diagram is shown in Fig. 3. A detailed description of the circuit has been given elsewhere by one of the authors.[11] The error in linearity of alternating output voltage as a function of d.c. modulation has been reduced to 1% by using the technique of envelope feedback. In addition, the output stage has an

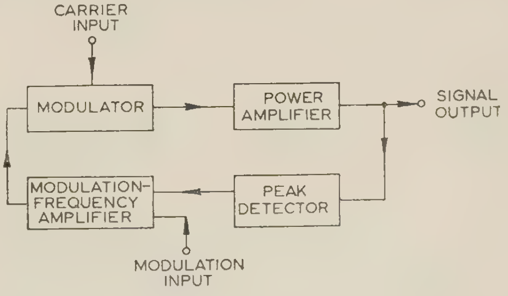

Fig. 3.—Amplitude-modulator block diagram.

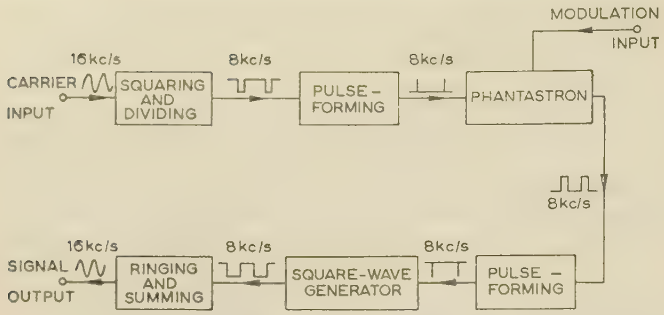

Fig. 4.—Phase-modulator block diagram.

nternal impedance of about 1 ohm, or 0·0002 per unit, such that it can be regarded as a constant-voltage source.

A second amplitude modulator is used to represent the infinite busbar, as shown in Fig. 2, and constitutes a load for the generator. In this case the modulation is a constant direct voltage equal to the busbar voltage.

(3.3.2) The Phase Modulator.

The range of phase shift required of this unit is about 270°, (+180°, −90°) and it is desirable that the deviation from linearity of the a.c. phase-shift as a function of direct modulating voltage should not be greater than about 2%. This range of phase shift is considerably greater than the phase swings produced by conventional phase modulators as used in communications, and various alternative electronic methods have been proposed. These alternatives are either very complex or employ a special tube not normally available in this country, such as the 2H21 Phasitron. A further possibility exists in the phase modulation which obtains as a direct consequence of frequency modulation.[12] This has the added advantage that a process of integration is inherent in the method by virtue of the integral relationship existing between phase and frequency modulation, and might conceivably dispense with one stage of analogue integration. A serious drawback to this technique would be the loss of crystal control over frequency unless either complicated frequency-stabilizing circuits were used or recourse was had to the F.M.Q. system,[13] which requires specially ground crystals.

By far the most promising technique is that which has been proposed in essence by Van Ness and Peterson,[6] in which a phase shift between two sinusoids of equal and constant frequency is considered as a time delay between corresponding cycles. Hence a linearly increasing time delay results in a linearly increasing phase shift. An accurate linear control over time delay can be produced by a Phantastron.[14] This is an electronic pulse-circuit in which time delay is a linear function of an applied direct modulating potential. Phase modulation therefore results by transforming the reference input sinusoid into a periodic pulse waveform which is delayed by the Phantastron, and this delayed waveform is then used to synchronize a sine-wave generator. The phase shift between the input and output sinusoids is therefore controlled by the Phantastron and hence is a linear function of the Phantastron modulating voltage.

It is characteristic of the Phantastron that the maximum time

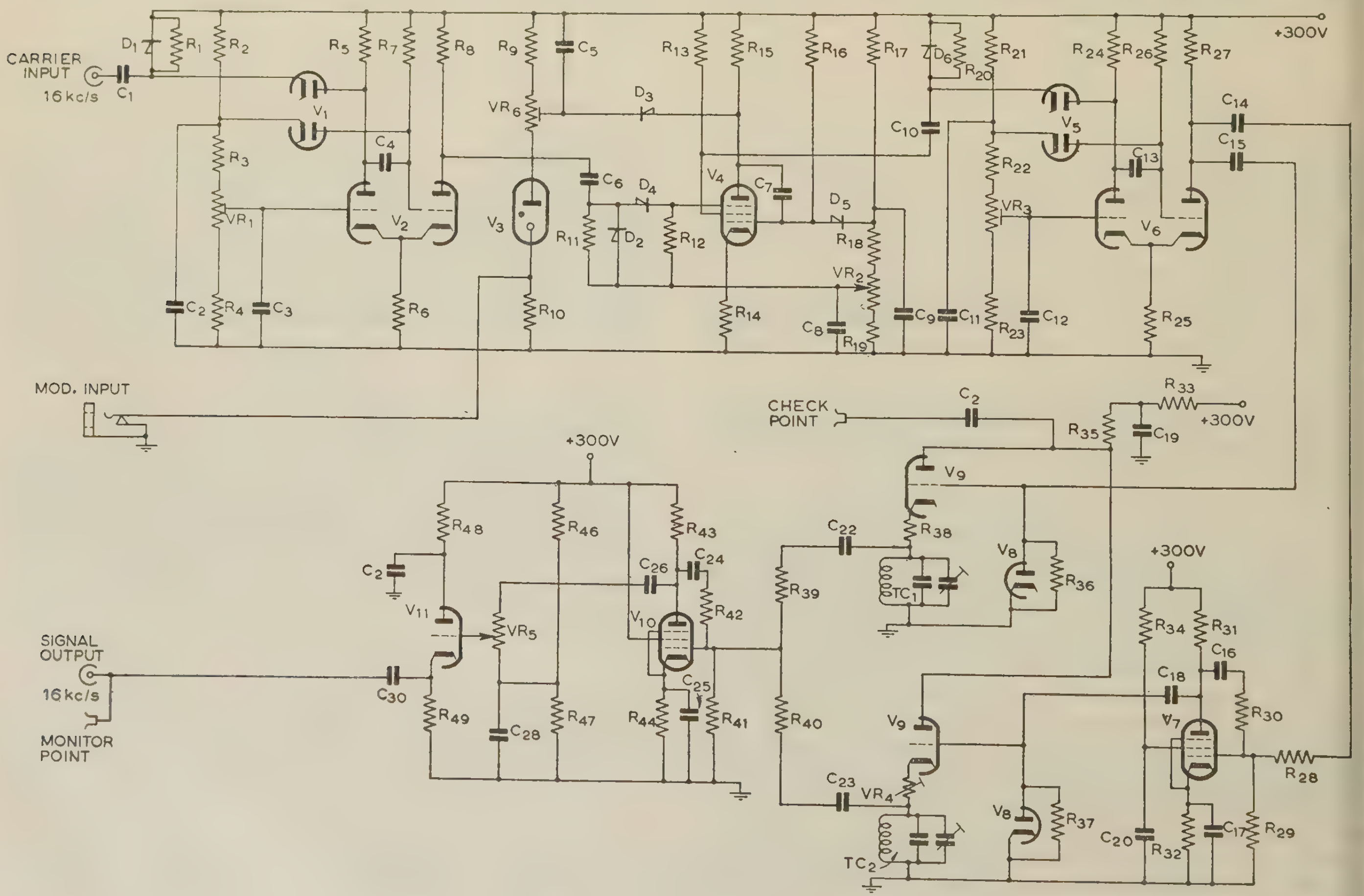

Fig. 5.—Phase modulator.

delay is limited to an interval somewhat less than one period of the trigger-pulse waveform. Thus, by employing a trigger-pulse frequency that is one-half of the base frequency of the impedance analogue, a total phase shift of about 550° at base frequency is obtained.

A phase modulator working on these principles has been developed; Figs. 4 and 5 are the block and circuit diagrams respectively.

In Fig. 5, the base frequency is halved by V2. The Phantastron, V4, is modulated by controlling the static potential of the anode from the modulating voltage via V3, a voltage-reference tube which adds a constant voltage to the modulation. A delayed pulse is derived from the screen waveform and triggers the 8 kc/s square-wave generator V6. A self-oscillating sine-wave generator is not used because of the difficulty of rigidly synchronizing such a circuit, and the base-frequency sine-wave is restored by means of the ringing and summing stages V9 and V10. This is a simple circuit which avoids the use of a multi-section filter. The principle of the ringing circuit is well known[14] and is a basic source of a pure sine-wave, provided the damping in the ringing circuit is small. This is ensured by the use of high-Q-factor inductors, wound on small Ferroxcube pot cores, for the tuned circuits TC1 and TC2, each resonating at 15·915 kc/s. These are caused to ring for one cycle, in alternate sequence, by the paraphase square waves from V6 and V7. The waveforms from TC1 and TC2 are summed in V10 to produce a continuous sine-wave, the phase of which is controlled by the modulating voltage.

The complete phase modulator has been checked for linearity and the error over a range of 400° is less than 2%, which was the limit of accuracy of the available phase-measuring apparatus.

VR6 and VR2 are the coarse and fine zero-set controls respectively; VR6 is normally pre-set since it also affects the modulator sensitivity.

Referring to Fig. 2, the modulating voltage Kδ is derived from the output of the last integrator via a variable-gain scaling amplifier of gain K, which serves a dual function. For a given setting of the control VR6 in Fig. 5, the desired modulator sensitivity, expressed in degrees per volt, can be adjusted by varying K, which is done in practice by adjusting a ten-turn potentiometer. This amplifier is also used for setting-in the initial-condition value of rotor angle δ^*, as shown in Fig. 2.

Under operating conditions the phase modulator is adjusted to provide phase-shifts of approximately 90° in the negative direction and about 450° in the positive direction.

(3.3.3) **Circuits for the Derivation of i_d and i_q.**

These currents are, by definition, the components of generator load current i along the direct and quadrature machine axes respectively, as indicated in Fig. 1. Thus if θ is the angle between the load current vector and the quadrature axis,

$$i_q = i \cos \theta \qquad \ldots \ldots \ldots \quad (9)$$

$$i_d = i \sin \theta \qquad \ldots \ldots \ldots \quad (10)$$

$$= i \cos (\theta - 90)$$

A circuit using a wave-chopping technique[15] has been developed, which provides a direct voltage output proportional to the product $i \cos \theta$, where i is proportional to the amplitude of the chopped sinusoid, and θ is the phase angle between this sinusoid and the fundamental component of the gating square wave. The circuit which provides $i \sin \theta$ is similar in all respects, with the exception that the phase of the gating square wave is advanced by 90° as required by eqn. (10). The block diagram is shown in Fig. 6, in which both i_d and i_q circuits are shown.

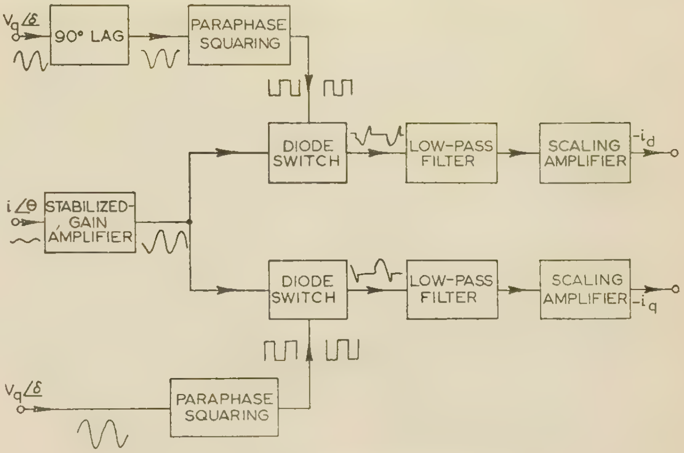

Fig. 6.—i_d and i_q circuits, block diagram.

The sinusoidal voltage from the current-shunt (Section 3.2) is amplified 100 times in a stabilized-gain amplifier, which is common to both circuits. The alternating voltage V_q, which represents a vector lying along the machine quadrature axis, is converted into a square wave by a process of successive clipping and amplification. A paraphase square wave is also developed and the two square waves are applied to a diode switch[16] which gates the transmission of the amplified current sinusoid. The output waveform from the switch is filtered and the d.c. component extracted and scaled in the d.c. amplifier.

The 90° phase advance for the i_d circuit is obtained by first creating a 90° lag in the V_q waveform and then introducing a 180° lead by reversing the connections from the diode switch to the paraphase square waves.

Fig. 7 is the circuit diagram of the i_d circuit. As explained above, the i_q circuit differs only in the absence of the 90° lag circuit of V1.

The stabilized-gain amplifier V_6–V_9 is a 3-stage feedback circuit with a loop gain of about 45 dB. The output stage has an internal impedance to transients of about 1 ohm, by virtue of the localized feedback loop of V8 and V9. V9 is direct-coupled to the diode switch. The gating waveforms are clamped by diodes D7 and D8 at about −10 volts and rise to about +60 volts. The rise and fall times are of the order of $\frac{1}{4}$ microsec. Dissimilarities in the conduction characteristics of the switch diodes, result in a square-wave output of small amplitude ($\simeq\frac{1}{4}$ volt) for zero input voltage to the switch from V9. This output can be minimized by optimum design values for the gating resistors R_{54} and R_{55}, and is finally compensated by means of a secondary input to the d.c. scaling amplifier which nullifies the mean level of this spurious output from the switch.

R_{61} and C_{46}, together with R_{62} and C_{48}, form the low-pass filter. Switch S_1 is used to enable the set-zero control in the scaling amplifier to be adjusted correctly.

The errors in linearity of i_d as a function of i and $\sin \theta$ have been measured and found to be less than 2% of unit output over the range 0–2 per unit.

(3.4) The Simulator Control Unit

The function of this unit is to co-ordinate the following switching sequence:

(*a*) Release the analogue computer from the initial-conditions state for a computation.
(*b*) Apply the short-circuit fault in the impedance analogue.
(*c*) Clear the faulted line.
(*d*) Reclose the line after removal of the fault.
(*e*) Restore the computer to the initial-conditions state when computation has ceased.

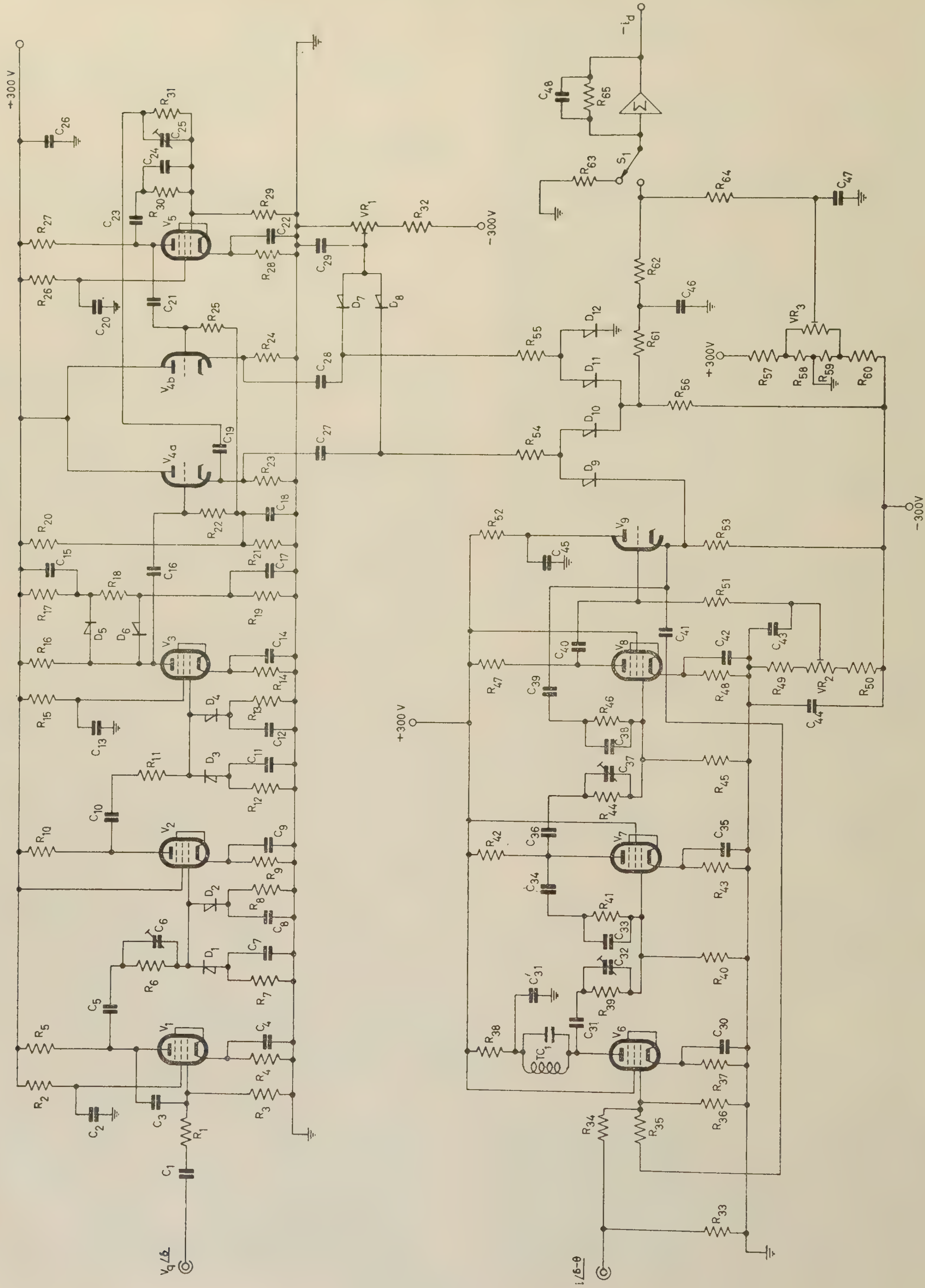

Fig. 7.—i_d circuit.

The simulator, as described, is operating on real time, and the intervals between the above operations are as follows. That between (*a*) and (*b*) is fixed at 1/10 sec; that between (*e*) and (*a*) fixed at 1 sec; that between (*b*) and (*c*), which corresponds to the clearing time, is variable in steps of 1/100 sec ($\frac{1}{2}$ cycle of 50 c/s) up to a maximum of 0·89 sec; that between (*c*) and (*d*), corresponding to the reclosing time, is variable in steps of 1/100 sec up to a maximum of 0·99 sec. The total time for the entire sequence is 5 sec.

Because of the number and variety of timing intervals involved, the switching impulses are derived from a simple electronic counting mechanism. This is driven from a pulse generator of known frequency. The various switching operations can be instigated by associating each operation with a particular count, which allows for simplicity of control over the timing intervals.

The counting mechanism employs four Dekatron tubes in a 4-decade counter, driven from a 1 kc/s pulse generator. By using pulse-coincidence switches,[17] initiating impulses can be derived from the Dekatrons, with timing accuracies of up to four significant figures which can be readily varied.

High-speed relays are used for line switching in the impedance analogue. These have operating delays of 1–2 millisec ($\simeq$1/10 cycle of 50 c/s) which can therefore be ignored compared with the delays introduced externally.

(4) SIMULATOR ACCURACY TESTS

For a completely rigorous test, a comparison should be made between the simulator solution of a typical line-fault problem and the theoretical solution. The introduction of finite field time-constant and line shunt-capacitance would render the theoretical calculation tedious. Consequently a series of three simpler tests has been conducted, each of which has a different bearing on the simulator. These are composed of a steady-state test, which checks the accuracy of scaling and linearity; a simple transient test, the solution of which can be compared with published normalized results; and a basic transient test on the integrators of the d.c. computer.

(4.1) The Steady-State Test

The steady-state test consists in recording the simulator solutions for machine power output and field-flux linkage as functions of rotor angle. The conditions of the test were those for a machine with zero armature resistance, connected via a purely inductive line to an infinite system, the machine open-circuit terminal voltage being maintained equal to the voltage of the infinite system. These conditions lead to simple analytical solutions[4] for power output and field-flux linkage, which can be compared with the simulator solutions. The errors between the two sets of solutions are less than 2%.

(4.2) Integrator Transient Tests

The integrators in the d.c. analogue were checked for scaling accuracy and phase shift by connecting them, two at a time, to solve a simple-harmonic-motion problem.[18] The $\sum/M$ scaling amplifier (see Fig. 2) was used as a sign-reversing amplifier for this test. It is a simple matter to calculate the natural frequency of the resulting oscillations in terms of the two integrator scale factors and the scale factor of the sign-reversing stage. The measured frequency was in error by less than 1% for the three integrators, and there was no detectable decrement or increment of amplitude after 100 cycles at 1 c/s.

(4.3) Simulator Transient Test

The simulator transient test is similar in substance to the simplified stability problem described in References 1 and 19, with the exception that in this case the entire simulator was used, subject to the assumptions required by the problem. This assumes that direct- and quadrature-axis synchronous and transient reactances are equal; that there is no machine resistance; that the transmission line is purely inductive; that there is zero damping; that constant field-flux linkage obtains; and that the machine open-circuit terminal voltage is equal to the voltage of the infinite system.

The computed stability boundary is shown, compared with the calculated marginal results of Reference 19, in Fig. 8.

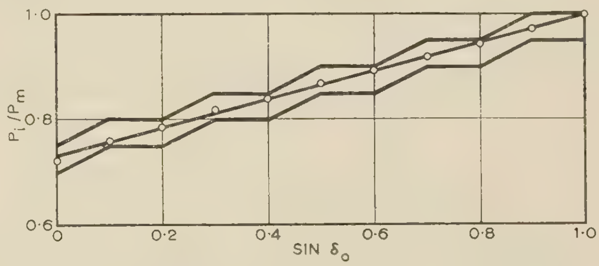

Fig. 8.—Stability boundary (shown thus o) for the simplified system compared with those of Reference 19.

(5) REPRESENTATIVE SOLUTIONS

Although the paper is concerned primarily with the description of an experimental simulator, it would be incomplete without some examples of the type of problem that can be solved with its aid. The problems have been selected to indicate the scope of the simulator.

(5.1) Sustained Fault: Comparison of Effects of System Parameters

The basic problem is similar to that chosen in Section 4.3 and used there as an accuracy test. The solutions presented in Fig. 9 show the effect on the stability boundary of the use of

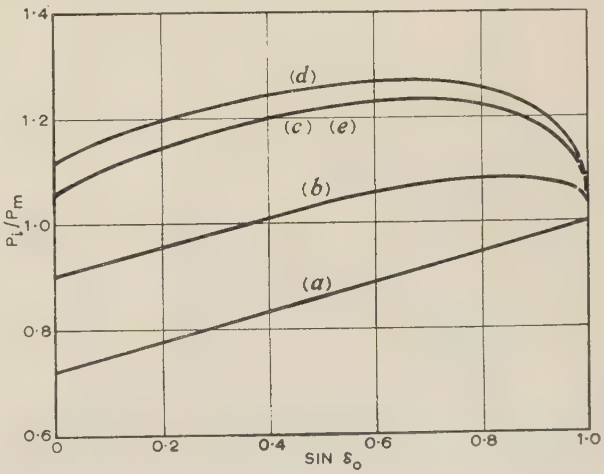

Fig. 9.—Effect of system parameters on the stability boundary of Fig. 8.

(*a*) Zero transient and synchronous saliency, constant field-flux linkage and purely inductive line, giving

$$X_{dm} = X_{qm} = X'_{dm} = 0\cdot4 \text{ p.u.}; \; V = v = 1\cdot0 \text{ p.u.}$$

(*b*) As in (*a*) but with finite transient saliency, giving

$$X_{dm} = X_{qm} = 0\cdot4 \text{ p.u.}; \; X'_{dm} = 0\cdot2 \text{ p.u.}$$

(*c*) As in (*b*) but with finite synchronous saliency, giving

$$X_{dm} = 0\cdot6 \text{ p.u.}; \; X_{qm} = 0\cdot4 \text{ p.u.}; \; X'_{dm} = 0\cdot2 \text{ p.u.}$$

(*d*) As in (*c*) but with finite armature and line resistance, giving

$$R_m = 0\cdot01 \text{ p.u.}; \; \frac{R_l}{X_l} = 0\cdot15.$$

(*e*) As in (*d*) but with finite field time-constant, giving

$$\tau_{d0} = 5 \text{ sec.}$$

system parameter values which are more typical than those assumed in Section 4.3. In Fig. 9 it is the ratio of total input power (after the step change) to maximum steady-state power that has been plotted an ordinate. The curves have been normalized with respect to maximum steady-state power, since it is considered that any gain or loss in transient stability is most clearly demonstrated in this way. It should be noted that the curve corresponding to a finite field time-constant represents the stability boundary for first swing only. Instability subsequent to the first swing has been observed, as described in Reference 1.

The dotted portions of these curves correspond to regions which are unstable in the steady state prior to the disturbance, and are therefore unrealistic. Such conditions can, of course, be set up on the simulator in the initial-conditions state when the integrators—which constitute the dynamic feedback path—are paralysed.

(5.2) Fault Cleared: Circuit Reclosed

The case considered is that of a salient-pole machine connected via a single-circuit line of 1·0 per unit inductive reactance to an infinite busbar. A balanced earth fault occurs at 0·1 per unit reactance from the generator terminals and, in Fig. 10, the stability boundary of power input as a function of reclosing time is plotted for both 6- and 9-cycle clearing. Line resistance and capacitance are presented as parameters.

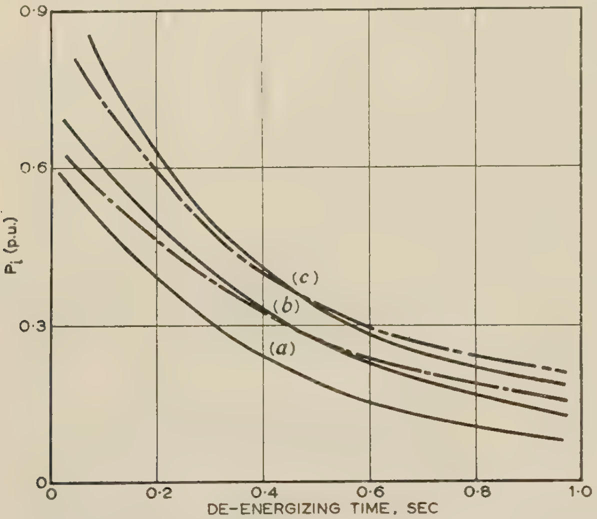

Fig. 10.—Stability boundaries for input power as a function of de-energizing time for a 3-phase fault close to the machine terminals.

— — — 9-cycle clearing.
———— 6-cycle clearing.

Transmission line represented by
(a) Series inductance only.
(b) Series inductance and resistance.
(c) Series inductance and resistance plus shunt capacitance.

The system constants used in the problem were as follows:

$H = 3$ kW-sec/kVA. $R_m = 0{\cdot}008$ per unit.
$\tau_{d0} = 5$ sec. $R_l = 0{\cdot}16$ per unit.
$X_{dm} = 0{\cdot}6$ per unit. Total shunt capacitance $= 1{\cdot}0$ per unit.
$X'_{dm} = 0{\cdot}2$ per unit.
$X_{qm} = 0{\cdot}4$ per unit.

(5.3) Pole-Slipping

The wide range of the phase modulator permits the display of the phenomenon whereby the machine resynchronizes after slipping a pair of poles. For a comprehensive study of this effect it would be necessary to adjust the range of the phase modulator so that the entire phase-shift was available in the positive direction (see Section 3.3.2).

Viscous damping must, of necessity, be introduced in order to dissipate some of the kinetic energy stored in the rotor during the period of slip. It is also essential that reclosing shall take place. Fig. 11 is an oscillogram of the damped oscillations of the rotor subsequent to resynchronism. The upper trace is the power-differential waveform; the three step-changes represent fault application, line clearing and reclosing, respectively.

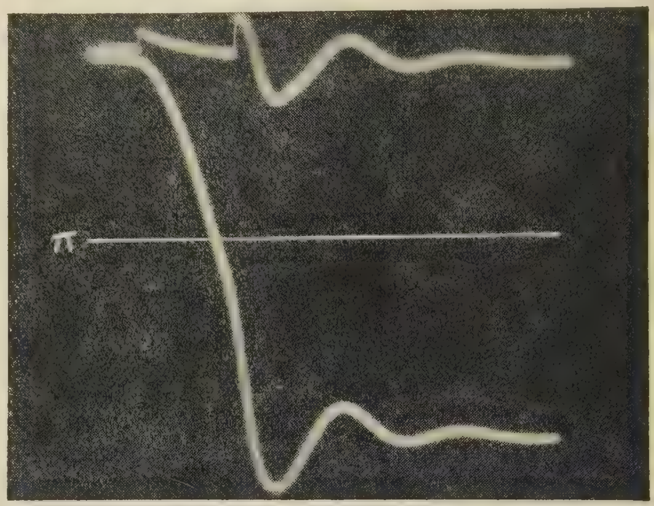

Fig. 11.—Oscillograph of power differential and rotor angle during and subsequent to resynchronizing after slipping a pair of poles.

(6) CONCLUSIONS

The system simulator which has been described is a laboratory tool containing techniques applicable to a multi-machine simulator. A number of the hitherto conventional assumptions concerning synchronous-machine characteristics have been avoided by the use of an electronic analogue computer. This will, additionally, greatly facilitate the incorporation of analogues for voltage regulators, prime-mover characteristics and magnetic-circuit saturation.

A high-frequency a.c. analogue of the transmission network has reduced the physical size of many of the constituent components of the simulator, and in conjunction with the electronic analogue of the synchronous machine will permit the swing frequency to be raised by fast time-scale operation. This will assist in the presentation of the system swing curve as a stationary trace on an oscillograph.

(7) ACKNOWLEDGMENTS

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(9) APPENDICES

(9.1) Synchronous-Machine Equations

Park's equations for an ideal synchronous machine are

$$v_{fd} = p\psi_{fd} + R_{fd}i_{fd} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$v_{dm} = p\psi_{dm} - \psi_{qm}p\Theta - R_m i_d \quad . \quad . \quad . \quad (12)$$

$$v_{qm} = p\psi_{qm} + \psi_{dm}p\Theta - R_m i_q \quad . \quad . \quad . \quad (13)$$

where

$$\psi_{fd} = X_{fd}i_{fd} - X_{ad}i_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$\psi_{dm} = -X_{dm}i_d + X_{ad}i_{fd} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$\psi_{qm} = -X_{qm}i_q \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Power output

$$P_0 = \psi_{dm}i_q - \psi_{qm}i_d \quad . \quad . \quad . \quad . \quad (17)$$

Application of the assumptions in Section 2 to eqns. (12) and (13) gives

$$v_{dm} = -\psi_{qm} - R_m i_d \quad . \quad . \quad . \quad . \quad (18)$$

$$v_{qm} = \psi_{dm} - R_m i_q \quad . \quad . \quad . \quad . \quad (19)$$

By elimination of i_{fd} between eqns. (14) and (15),

$$\psi_{dm} = \frac{X_{ad}}{X_{fd}}\psi_{fd} - \left(X_{dm} - \frac{X_{ad}^2}{X_{fd}}\right)i_d \quad . \quad . \quad . \quad (20)$$

Eqn. (20) introduces the concept of transient reactance X'_{dm} defined by

$$X'_{dm} = X_{dm} - \frac{X_{ad}^2}{X_{fd}} \quad . \quad . \quad . \quad . \quad . \quad (21)$$

and a quantity Ψ_{fd} proportional to field flux linkage

$$\Psi_{fd} = \frac{X_{ad}}{X_{fd}}\psi_{fd} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

A voltage V, proportional to field current, is now defined as

$$V = X_{ad}i_{fd} \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

Thus, from eqns. (14), (23), (21) and (22), there is

$$V = \Psi_{fd} + (X_{dm} - X'_{dm})i_d \quad . \quad . \quad . \quad (24)$$

and from eqns. (11), (22) and (23)

$$X_{ad}\frac{v_{fd}}{R_{fd}} = \tau_{d0}p\Psi_{fd} + V \quad . \quad . \quad . \quad . \quad (25)$$

The term $X_{ad}\frac{v_{fd}}{R_{fd}}$ is the open-circuit excitation voltage and is denoted by V_{fd}; hence eqn. (25) can be rewritten

$$\Psi_{fd} = \frac{V_{fd} - V}{\tau_{d0}p} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

From eqns. (17), (15), (16) and (23) the expression for power output becomes

$$P_0 = [V - (X_{dm} - X_{qm})i_d]i_q \quad . \quad . \quad (27)$$

To simplify this expression it is convenient to introduce a voltage V_q defined by

$$V_q = V - (X_{dm} - X_{qm})i_d \quad . \quad . \quad . \quad . \quad (28)$$

Eqn. (27) then becomes

$$P_0 = V_q i_q \quad . \quad . \quad . \quad . \quad . \quad (29)$$

(9.2) Derivation of Machine Terminal Voltage

Substituting for ψ_{dm}, from eqn. (15) into eqn. (19), and adding $(X_{qm}i_d - X_{qm}i_d)$ gives

$$v_{qm} = X_{ad}i_{fd} - X_{dm}i_d - R_m i_q + (X_{qm}i_d - X_{qm}i_d) \quad (30)$$

$$= V_q - R_m i_q - X_{qm}i_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Substituting for ψ_{qm}, from eqn. (16) into eqn. (19) and multiplying throughout by $-j$ gives

$$-jv_{dm} = -jX_{qm}i_q + jR_m i_d \quad . \quad . \quad . \quad (32)$$

Adding eqns. (31) and (32), and using eqns. (6) and (7) we get

$$v_{tm} = V_q - R_m(i_q - ji_d) - jX_{qm}(i_q - ji_d) \quad . \quad (33)$$

$$= V_q - (R_m + jX_{qm})i \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

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TRANSMISSION AND DISTRIBUTION AT 66kV AND OVER: OVERHEAD LINES

A Review of Progress

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(1) INTRODUCTION

Since the last Review of Progress* the design and construction of overhead transmission lines have continued to advance in step with the ever-growing levels of power to be transmitted and the ever-increasing distances of transmission. Although this review is intended to be mainly concerned with the higher-voltage lines (66kV and above) there have, of course, in the last 17 years, been advances in design or modifications to earlier practice which chiefly concern lower-voltage lines but which nevertheless impinge upon the general higher-voltage field.

The review deals first with technical and other considerations relating to transmission-line materials, components and designs, and later with more general aspects and future possibilities.

(2) CONDUCTORS

(2.1) Materials, Construction and Tensioning

Except for part of the war period, when aluminium was effectively diverted for other purposes, the use of copper for overhead-line conductors has decreased, and continues to decrease, owing to its high basic price relative to its chief competitor, aluminium, and to its adverse effects on tower costs, especially for the higher voltages. Steel-cored aluminium (s.c.a.) continues to be, in general, the most economical conductor in view of its relatively low cost and high tensile strength; at voltages at and over say 132kV, where corona considerations favour large overall diameter, steel-cored aluminium, for a given equivalent cross-section, has obvious advantages over copper. In certain fields, high-tensile aluminium-alloy conductors, without steel cores, find a degree of economical application.

For s.c.a. conductors between about $0\cdot125$ and $0\cdot25\,\mathrm{in}^2$ (equivalent), British practice favours the 30/7 (30 aluminium over 7 steel) stranding, but for still larger sizes considerations of steel-tower economics and design of tension insulator sets begin to set limits to the advantages of extremely high conductor strength. For conductors in the region of $0\cdot3\,\mathrm{in}^2$ (equivalent) and over, the 54/7 construction is therefore favoured. Some investigations are being made into the possibilities of very large s.c.a. conductors of hollow construction and with a smooth cylindrical exterior, but so far there seems little reason to depart from the ordinary stranded cable.

The British Standards for overhead line conductors (B.S. 125 for copper, B.S. 215 for steel-cored aluminium and B.S. 672 for cadmium-copper) have all been revised in the last few years. Revisions are generally in the direction of reducing the number of different standard sizes and of incorporating the effects on tensile strength, conductivity, etc., of modern wire-manufacturing methods.

Under the great majority of service climatic conditions, the galvanized-steel cores of s.c.a. conductors (without other protection) are found to have an indefinitely long life, and corrosive effects between the aluminium and the zinc are negligible. In certain industrial and sea-coast areas, however, this is not so, and conductor life may be seriously shortened by direct or electrochemical corrosion effects between the aluminium and the core. The subject has been dealt with by Forrest and Ward,[1] who conclude that greasing of the steel core, and in some cases of the aluminium wires as well, is likely to be an effective preventative of trouble. Greasing of the steel core, at least, is now tending to become standard practice.

The distribution of tensile stress between components of composite conductors under various conditions is the subject of E.R.A. Reports.[2] Questions of sagging and tensioning of conductors as affected by factors of safety (or desirable safety margins), and statutory regulations have been discussed by Boyse and Simpson[3] and Grimmitt.[4]

(2.2) Conductor Vibration

The twofold problem—vibration itself, and vibration troubles and their prevention—continues to be actively studied in many parts of the world. An E.R.A. Report[5] provided a general review of the subject in 1940.

Generally speaking, vibration tends to be heaviest and liability to conductor vibrational fatigue most serious with conductors of large diameter/weight ratio, of high tensile strength and therefore high 'everyday tension', and of materials not ideal from the fatigue point of view. Steel-cored aluminium (otherwise so advantageous) is therefore unfortunately liable to vibration trouble, and reports of world experience of such trouble are largely associated with this type of conductor.

In America, s.c.a. conductors are usually equipped with armour rods at the suspension clamps. These undoubtedly give a large measure of protection to the conductor against vibration fatigue, but have very little effect in damping out vibration itself. In Great Britain, the major lines have always been equipped with vibration dampers of the Stockbridge type, without any special conductor protection at the clamps. The efficiency of the dampers in practically eliminating vibration altogether has been proved by something over 500 000 conductor-mile-years of successful experience, and there is therefore little likelihood of change in British practice.

When anti-vibration devices are not used, the probability of ultimate vibration trouble is largely a function of the 'everyday stress' or, for a particular conductor, of the 'everyday tension' in the conductor. These terms do not admit precise definition, but the 'everyday tension' may be broadly described as 'that general order of tension which exists in a conductor for 99% of its life'. Vibration amplitudes are usually greatest under very light wind conditions and negligible under conditions of high wind with or without ice loading. From the vibration point of view, therefore, the everyday tension is of importance; especially in countries where ice conditions do not occur, the stringing of a conductor as tightly as local statutory regulations permit may result in undesirably high everyday tension. Research and co-ordination of world experience continue and may some day lead to guiding recommendations of the form—'In order to guard against vibration troubles the everyday tension in such and such a conductor (except with efficient dampers) should not exceed X'.

* Sharpe, F. H., Lovell, A. J., and Fennell, W.: 'Transmission and Distribution', *Journal I.E.E.*, 1941, 88, Part I, p. 257.

Mr. Ryle is with Merz and McLellan.

(2.3) Current-Carrying Capacity

The power-transmission capacity of a long, high-voltage line is usually limited by considerations of voltage regulation and system stability. On relatively short higher-voltage lines (under, say, 50 miles), however, large power transfers involve no voltage regulation or stability problems, and it may be possible and occasionally expedient to run the line up to the safe thermal limit of the conductors. The safe thermal limit of a given conductor is no hard-and-fast quantity, depending as it does upon

(*a*) The temperature at which annealing of the hard-drawn wires is supposed to occur.
(*b*) The ambient air temperature.
(*c*) The minimum surrounding air velocity.
(*d*) The level of solar radiation.
(*e*) The condition of the conductor surface.

With the exception of (*a*), all of these, for any particular project, are largely matters of assumption. E.R.A. Report Ref. O/T5 (Reference 6), describes investigations into the subject and concludes with useful tables and curves giving current-carrying capacities of various conductors based on practical assumptions.

(3) INSULATORS

(3.1) Materials and Design

In the previous review by Sharpe *et al.*, brief mention was made of toughened-glass insulators, which were then under service trial in limited quantities. The toughened-glass insulator is now firmly established and is used in very large numbers on the British system, at all voltages up to and including 275 kV. Large quantities are also in use abroad, notably in South Africa and on the Swedish 380 kV system; these insulators will also be used on the Kariba 330 kV lines.

Toughened glass has by no means ousted porcelain in the high-voltage insulator field. The price differential in favour of the former is usually small, and competition between the two materials is likely to remain keen, although toughened glass has certain slight advantages over porcelain in increased electrical puncture strength, higher resistance to thermal effects such as those caused by power arcs, and decreased liability to fracture in handling and erection. A very practical advantage is that, if an insulator unit fails in service from any electrical or mechanical cause, the outer disc disintegrates and falls away whilst the glass remaining between the cap and the pin retains practically full mechanical strength; the line therefore remains mechanically sound, but the defective unit can at once be detected visually from the ground. For various papers and reports on toughened glass insulators see References 7, 8 and 9.

Apart from continuous improvement in manufacturing processes, etc., and in high-strength designs, no particular development in porcelain line insulators is to be noted. The performance of line insulators under conditions of fog and industrial and other deposits is largely a matter of surface distribution of such deposits.[10] Irregularities in the skin resistance may set up voltage-distribution conditions favourable to flashover, even at normal working voltage. Certain developments[11] have been made in 'semi-conducting glaze', the effects of which are to stabilize to a large degree the surface voltage distribution. Largely owing to certain difficult 'end-effects' between the glaze and the metal parts, this otherwise promising development has not so far been taken beyond limited service trials.

B.S. 137, for porcelain and toughened-glass insulators, was introduced in 1941, and a new revision will shortly be published. In the 1941 edition the higher-duty insulator units were for [illegible]000 and 8 000 lb working loads; the new revision includes [illegible]2 000 lb units. The standardization of interlinking ball-and-socket fittings for all three sizes of unit is a noteworthy feature; another is increased emphasis on electrical impulse tests.

(3.2) Insulator Fittings

In the early days of high-voltage lines, say 1920–30, the realization that voltage distribution over a long insulator string was necessarily far from uniform led to the widespread use of guard-rings at the line end. For ideal clean conditions there is no doubt that such rings can achieve a considerable degree of voltage-distribution control, but it is now accepted that the adverse effects of irregular surface deposits on the insulators can entirely mask or nullify the beneficial effects of guard-rings. Guard-rings, with their wide transverse dimensions, mean correspondingly increased cross-arm dimensions in order to provide necessary live-metal clearances. The general practice at present is therefore simply to provide arcing horns at the live end, their main purpose being to protect the conductor from power arcs following flashover. At the highest voltage levels, the arcing horn may take the form of an elongated ring with narrow transverse dimensions, or may embody relatively small annular appendages. Such departures from simple horns are usually only required for keeping down electrical stresses at the clamps or elsewhere which might otherwise give rise to corona and radio interference.

For s.c.a. conductors, general practice favours compression clamps for tension insulator sets; the 'snail' clamp, of which many thousands have given excellent service for many years, has been found to be unsatisfactory with the comparatively recent introduction of greased-steel cores (see Section 2.1).

Some investigations have been made into the advantages of aluminium-alloy suspension clamps, instead of the usual ferrous clamps, from the point of view of reducing losses (due to eddy currents in the clamps). However, it is found that, unless the line-conductor electrical loads are reasonably heavy and maintained, the higher cost of the alloy clamps is not offset by the savings due to reduced losses.

(4) SUPPORTS

(4.1) Wood Poles

B.S. 1990: 1953, apart from general technical revisions, effectively combines and supersedes the earlier separate British Standards, B.S. 139 and B.S. 513, for red fir and European larch poles. Wood poles are little used for lines at over 66 kV, although at 132 kV, for single-circuit fairly small conductors at horizontal spacing and no earth conductors, a marginal economic case for their use can be made out.

(4.2) Reinforced-Concrete Poles

Especially during and immediately after the 1939–45 War, the shortage of wood poles encouraged the development of reinforced-concrete poles. Owing to limitations of easily transportable lengths and weights, the use of reinforced-concrete poles is usually confined to lines of not exceeding 66 kV. B.S. 607: 1951 is the latest revision of the British Standard for reinforced-concrete poles. Reference 12 is relevant, and various aspects of reinforced concrete for overhead lines are also treated in Reference 13.

(4.3) Steel Towers

Largely owing to the height limitations of wood or concrete poles commercially available, steel towers hold the field for all double-circuit lines for 66 kV or above, and for all major lines, single or double circuit, at 132 kV and above. No special developments in general outline design are to be reported; taking into account foundation costs, the wide-base design

proves generally economic. For towers with a single central earth conductor, the tower body is of normal pyramidal outline; for single-circuit towers with flat conductor spacing and two earth conductors (as used in bad lightning districts abroad) the economical shape of tower body is the 'waisted' design. The advantages of the 'rotated' type of tower base are still questionable and are largely a function of the ratio of the normal transverse design loadings to the abnormal longitudinal and torsional loadings which may be assumed under broken conductor conditions. In general British practice, the 'rotated' base is rarely found to be justifiable. Various aspects of steel-tower economics, including a simple formula for pre-estimation of tower weights for normal and abnormal conditions, have been considered in Reference 14.

In the past, the use of high-tensile steel in tower work was often considered in view of the appreciable reductions in tower weight which could be made, but the relative cost per ton of high-tensile as compared with ordinary structural steel was such that little or no financial benefit was possible. At present, the costs per ton of the two types of steel are much closer and considerable economies are nowadays made in tower costs, as well as weights, by using high-tensile steel for all the more highly-stressed members. Aluminium alloys have been seriously considered for towers; tower weights could be reduced very materially indeed, but the cost per ton of suitable alloys is still such as to make the idea quite uneconomical. Justification for aluminium-alloy towers is only likely to be approached for lines in very remote and difficult mountain country where normal methods of transport are quite impossible.

Most members in a transmission-line tower are called upon to act as struts. Normal practice is, of course, to make members from standard rolled-steel equal-angle sections, with their clear advantages of easy fabrication and simple member-to-member joints. However, weight for weight, the tube is fundamentally much superior to the equal angle as a compression member, and much work is being done on the design of towers made wholly or partly of tubes. This is especially so in Italy and other Continental countries, where, owing to the steel shortage, the emphasis has been on saving of steel, even when saving in cost is not apparent. Tubes cost considerably more per ton than angle sections. As a rough general picture, towers made from tubes are not likely to be financially attractive unless the cost per ton of tubes can be kept below some 30–40% above the cost per ton of angles. Joints between tubular members are awkward and expensive to fabricate, and, apart from this, tubular members introduce serious galvanizing difficulties. The exterior galvanizing of hermetically sealed (e.g. by welding) tubes is a bad and, in fact, dangerous practice. On the other hand, if the tube ends are left open it is difficult to ensure sound galvanizing all over the interior, and it is also difficult to combine end openings with mechanically sound and cheap end connections. The problem is not yet satisfactorily solved. An E.R.A. Report[15] discusses in some detail various aspects of high-tensile steel and tubular-member construction, and of painting versus galvanizing. British practice continues to favour galvanizing of towers. Reference 16 should be consulted for an up-to-date review.

A modern trend in tower specification is to ensure that assumed loadings (with reduced factor of safety) for 'broken conductor conditions' are not such as to overweight the designs. For strain towers, fairly heavy assumed broken-conductor loadings add little to tower weights, and since such towers are numerically in a minority the effect on the total line cost is not appreciable. The margins of longitudinal and torsional strength available are very valuable, first during conductor erection (often of three or more conductors at a time), secondly for facilitating future line diversions, and lastly for limiting line damage consequent on any major disaster. For straight-line towers, which are numerically important, it is normal practice to allow for unbalanced longitudinal load effects corresponding to any one conductor only. In Great Britain and elsewhere, where ice loading is a fairly frequent condition, it is customary to assume a static longitudinal load equal to the maximum specified conductor tension, but reduced by a largely arbitrary factor to allow for the beneficial effects of suspension insulator swing. It is admitted that actual conductor breakage is rare, but the effects of very heavy unbalanced ice loadings and their sudden and uneven release on melting may be comparable in magnitude thereto. For countries where no ice-loading conditions occur, straight-line towers can be given adequate margins of longitudinal and torsional strength, at negligible cost, by specifying a longitudinal load, at any one conductor attachment, equal only to the everyday conductor tension.

British practice in the checking of tower designs continues rightly to rely on full-scale tower tests, wherever possible.[17]

The subject of adhesion between bare steel and concrete has, of course, been well explored for many years, but it has been debated what reliance could be laid on adhesion between galvanized-steel tower foundation stubs and concrete. The matter can now be considered as being on a sound basis following an E.R.A. Report.[18]

(5) TYPES OF LINE

(5.1) Multiple Conductors

With universal post-war tendencies towards transmission of greater blocks of power over longer and longer distances, economics have led towards line voltages well over the 220 kV level. At such high voltages one of the main problems is that of corona and the losses inseparable therefrom, and, what is rapidly becoming more important, the associated possibilities of interference with radio and television. At the highest voltages, in order to keep corona down to unobjectionable levels, the line conductors must either be single, but of very large diameter, or multiple, but of economic and manageable size. The idea of multiple conductors is not new, having been suggested by Thomas in 1909 and explored in considerable technical detail by Markt and Mengele and Edith Clarke in the years 1932–35. Apart from the fact that multiple conductors much ease the general corona problem, they offer reduced line inductance and increased shunt susceptance with correspondingly increased power-transmission capacity and stability. Other things being equal or equivalent, a multiple-conductor line costs more than the corresponding single-conductor line, but, certainly at the higher voltages, the extra cost is justified by the higher level of power transmissible. It is still debatable at what voltage levels it actually pays first to depart from single conductors and secondly to go beyond twin conductors. The following table is illustrative, if nothing else.

Up to 230 kV.	General world practice favours single conductors; but several Italian-built 220 kV lines have twin conductors.
275–330 kV.	Generally twin conductors; but original United States Boulder Dam 287 kV line used single hollow copper and certain modern American lines use single large s.c.a. conductors.
Over 330 kV.	Swedish, French and British (future) 380 kV lines use twin conductors; some Swedish lines are designed so that a third conductor could be added for some future higher voltage. U.S.S.R. 400 kV lines use triple conductors. German 400 kV lines use quadruple conductors.

The spacing between the component conductors of multi-conductor lines is usually a compromise between the spacing

giving theoretical optimum corona characteristics and some larger spacing which could itself be considered as a compromise between increased line cost and increased power-transmitting capacity. The result, depending largely on voltage and component conductor diameter, is usually in the region of 12–20 in, and necessitates spacers in the span. To allow for relative longitudinal movements of the component conductors under wind and/or ice conditions, the spacers must be either articulated or semi-flexible, and, if the former, they must be made so that no wear or rattling can develop in the articulations. The maximum permissible distance between spacers in the span is necessarily a matter of field experience. So far, neither the design nor the distribution of spacers can be regarded as having reached finality.

(5.2) Number of Circuits

It is, of course, evident that two separate single-circuit lines are together more reliable than one double-circuit line; for any normal types of design, however, the latter is the cheaper. In countries where lightning is a serious feature, the double-circuit line is at a great disadvantage since a direct stroke to an earth conductor or tower may mean a simultaneous two-circuit fault; single-circuit lines are therefore general practice.

Where the incidence of lightning is not very severe, and especially where the system is much interconnected, the double-circuit line is becoming more favoured. Apart from its lower cost, it only requires one route; especially in much developed countries like Great Britain, the finding of routes acceptable to all parties is becoming increasingly difficult. Single routes are obviously preferable, too, through forests, over partly built-up or otherwise valuable land and through narrow steep-sided valleys which frequently already accommodate a river, a road, a railway and communication lines, or a combination of some of these.

(6) LIGHTNING PERFORMANCE

Lightning, being a phenomenon very fortuitous in time, space and severity, has effects on line performance which are naturally only roughly predictable. The performance statistics from a large system do, however, become very valuable when the product, i.e. year-miles, of operation becomes considerable. The paper by Forrest,[19] together with the discussion, forms an important contribution to this subject as far as British lightning experience is concerned. The E.R.A. has issued several valuable Reports on the general subject of lightning and its effects on electrical systems,[21] and the general subject of lightning protection of high-voltage systems has been well discussed by Lacey,[20] and by Thomas and Oakeshott.[22]

For many years the lightning performance of high-voltage lines has been pre-estimated, with a fair degree of correctness and consistency, by the use of simple formulae involving only assumed isoceraunic level, stroke currents, footing resistances and insulation levels. In the last two or three years experience, notably in the United States, has indicated that for double-circuit lines in the 300 kV region such pre-estimation can err very appreciably on the optimistic side. Double-circuit 300 kV towers are generally in the region of 150 ft in overall height, which is some 50% greater than the general heights of double-circuit 132 kV or horizontally-spaced single-circuit 220 kV towers, for example. It seems likely, therefore, that the effects of tower height and, possibly, general tower outline in increasing vulnerability to lightning may be more serious than normally thought. Extended statistical results of service experience with double-circuit lines in the region of 275 kV and above, when available, will therefore be of special interest.

(7) GENERAL

(7.1) Regulations

It has been generally recognized for several years that the Overhead Line Regulations El.C53 (1947 Revise) are out of date, and various piecemeal *ad hoc* relaxations and modifications which have been issued from time to time have been found necessary to meet the needs of the rapidly growing supply industry. The need for completely new Regulations was well ventilated in the paper by Grimmitt[4] and the ensuing discussion. Since the dissolution of the Electricity Commissioners in 1947 the legal position relating to the issuing of new Regulations has been obscure, but is now regularized by the Electricity Act of 1957. The drafting of new Regulations is at present in an advanced state.

It may be remarked here that, in the United Kingdom, except for compliance with specified minimum clearances to earth, no special precautions at all are now demanded by the Regulations at road or other crossings; there are no requirements for reduced span lengths, increased factors of safety, duplicate conductors, duplicate insulators or increased insulation, or earth bars. This complete absence of restrictive requirements at crossings, in such a populous and developed country as the United Kingdom, sets an example to many other parts of the Commonwealth and the world in general, where expensive and needless precautions at crossings are still sometimes demanded. Notwithstanding all this, British Railways are in a position to insist on special measures at railway crossings. In particular, clearances very considerably greater than Regulation requirements may often be necessary in order to ensure adequate space for the erection, operation and maintenance of railway-electrification overhead equipment.

(7.2) Electrical Characteristics of Overhead Lines

In the period 1950–53, the E.R.A. produced a Report[28] on the electrical characteristics of overhead lines. For many years there had been a need for an authoritative compendium on the subject, giving all necessary information relevant to British practice in general and British Standard conductors in particular, and the Report very adequately satisfied the need. It is in three parts dealing, respectively, with (*a*) line performance under balanced conditions, (*b*) line characteristics under unbalanced conditions and (*c*) corona, multiple conductors and voltage regulation. Basic methods of calculation are fully presented and their application is illustrated by well-chosen examples. Wherever possible, all information capable of immediate practical application is given in the form of tables and charts.

The full Report mentioned above naturally includes much detailed and mathematical matter, which, although essential for a complete study, is rarely required in practical engineering work. A condensed Report Ref. O/T4A was therefore made available which summarizes the main Report, together with those tables and charts likely to be of immediate practical use.

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A GENERALIZED LOCUS DIAGRAM FOR INDUCTION MOTORS

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SUMMARY

It is well known that the construction of the induction-motor circle diagram presupposes the motor characteristic resistances and reactances to be constant. The paper discusses the variation of these circuit parameters and its influence on the current locus. It also provides a physical picture of conditions at starting and a simple technique for the construction of new 'output' and 'torque' lines, from which the machine performance may be computed over the whole speed range. The reliability of the method is indicated by comparison with experimental data.

LIST OF SYMBOLS

s = Slip.
V = Equivalent stator voltage per phase, volts.
I = Equivalent stator current per phase, amp.
I_f = Full-load stator current per phase, amp.
I_s = Starting current per phase, amp.
${}_{pu}I$ = Per-unit current = I/I_f.
X_1 = Equivalent leakage reactance of stator winding, ohms.
x_2 = Rotor leakage reactance referred to stator, ohms.
X = Total equivalent leakage reactance, ohms.
X_f = Total equivalent leakage reactance at full load, ohms.
${}_{pu}X$ = Per unit reactance = X/X_f.
R_1 = Equivalent stator resistance, ohms.
r_2 = Rotor resistance referred to stator, ohms.
r_{20} = Rotor resistance at standstill referred to stator, ohms.
R_e = Total equivalent resistance = $R_1 + r_2/s$, ohms.
R_{e0} = Total equivalent resistance at standstill = $R_1 + r_{20}$, ohms.
${}_{pu}R$ = Per unit resistance = R_e/R_{e0}.
m = Rotor to stator resistance ratio = r_2/R_1.
m_0 = Rotor to stator resistance ratio at standstill = r_{20}/R_1.
u = Output parameter = $(1 + m)/(1 + m_0)$.
w = Torque parameter = $1/(1 + m)$.

(1) INTRODUCTION

It is well known[1,2] that the construction of the induction-motor circle diagram (Heyland circle) presupposes the motor characteristic resistances and reactances to be constant. This means that the circle diagram is valid only when the motor is magnetically unsaturated and when the rotor conductors show no significant amount of skin effect at the supply frequency. When these two conditions are satisfied we may take the network shown in Fig. 1 as a simplified equivalent circuit of a 3-phase induction motor,[2,8] in which the shunt elements representing the magnetizing impedance are temporarily omitted. Then, assuming the voltage V and all resistances and reactances to remain constant while the slip s is allowed to vary, the current locus will be of the familiar semicircular shape shown in Fig. 2. The points 0, S and A correspond to zero, unit and infinite slip respectively.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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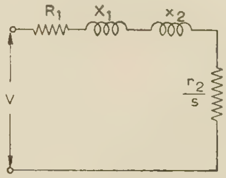

Fig. 1.—Simplified equivalent circuit of 3-phase induction motor.

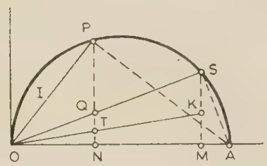

Fig. 2.—Circle diagram of induction motor.

If, however, the resistive and reactive components cannot be assumed to remain constant as the slip—and hence the current—varies over a wide range, then the semicircular current locus in Fig. 2 becomes distorted in a manner which is briefly touched upon in the relevant literature.[1] The difficulty of constructing and properly interpreting such a distorted current locus has deterred many engineers from using the circle diagram of induction motors in their work. Yet, in the opinion of the authors, these obstacles can be overcome, notably by the method outlined in the paper. The educational value of the locus-diagram approach to asynchronous-machine analysis, and its use as a designer's tool, need not therefore be lost.

(2) SATURATION EFFECTS

The usual classical methods of calculating the leakage reactance are based on the assumption that the number of ampere-turns which drive the leakage flux through the air-gap and the iron are those developed at full load. These calculations yield good values for normal running conditions, but at higher currents the ampere-turns are increased also, and the paths for the zigzag flux and tooth-lip flux become saturated relatively quickly (especially if the rotor slots are closed and/or the air-gap is small). It follows then that under these circumstances the reactance must be a function of the current. Fig. 3 shows typical curves of per-unit reactance, ${}_{pu}X$, plotted against per-unit current, ${}_{pu}I$, for 4-pole machines of different sizes. ${}_{pu}X$ is based on the equivalent leakage reactance, X_f, of the machine at its rated full-load current I_f. Hence

$$ {}_{pu}X = X/X_f \qquad (1) $$

and

$$ {}_{pu}I = I/I_f \qquad (2) $$

Curves similar to those in Fig. 3 can always be derived for a given class of motor, and will then be valid for the particular geometrical pattern of their stator and rotor laminations, the length of air-gap used, the actual ratio between stacking length and diameter (i.e. the ratio of end-winding and slot leakage to

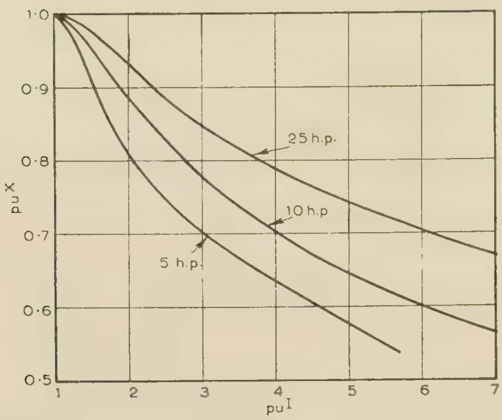

Fig. 3.—Variation of per-unit reactance with stator current in 3-phase 4-pole induction motors.

zigzag and tooth-lip leakage), and the ratio between the m.m.f. required to drive the leakage flux through the air (gap and slot openings) and iron (tooth-lips) and the total m.m.f.

Numerous ingenious methods are available for the calculation of leakage-path saturation,[3,7] but the uncertainty about their accuracy is considerable. Investigation shows, however, that for similar geometrical patterns of the laminations (i.e. slots of similar shape), and for the usual ratios between stacking length and diameter, the curve of ${}_{pu}X$ against ${}_{pu}I$ varies mainly with the output rating and speed of motors. Designers may therefore be inclined to rely on graphs based on empirical data in preference to theoretical analysis. In the paper the authors have used the curves in Fig. 3, which represent the mean variation of ${}_{pu}X$ observed in a number of different 4-pole machines; that they give quite reliable results will be seen later.

(3) CONSTRUCTION OF CURRENT LOCI

The diameter of the semicircle in Fig. 2 is determined by the effective reactance

$$X = X_1 + x_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Hence, if X varies, the diameter must change. Fig. 4 shows two families of circles: the first have their centres along the horizontal

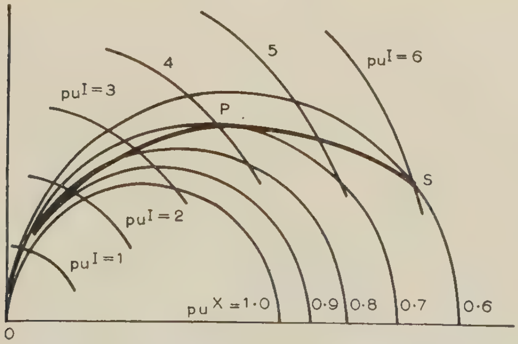

Fig. 4.—Current locus of induction motor with leakage-path saturation.

axis, and are for the range 0·6–1·0 p.u. reactance. Once the variation of ${}_{pu}X$ with ${}_{pu}I$ is known, e.g. as illustrated in Fig. 3, the 'distorted' current-locus of the induction motor may be superimposed on the family of semicircles in Fig. 4. Thus for a 10 h.p. 4-pole motor the point P on the modified current-locus, lying on the semicircle ${}_{pu}X = 0{\cdot}7$, must be at a distance OP from the origin equal to 4 p.u. current (in accordance with Fig. 3). On plotting a few further points in the same manner, the oval current locus in Fig. 4 is obtained. (A family of concentric circular arcs, with their centres at the origin, and representing per-unit currents marked on each one, has been included in Fig. 4 to assist in this construction.) It is noteworthy that the shape of the current-locus is entirely dependent on the graph in Fig. 3, and is in no way influenced by variations in the resistive circuit elements, due for example to skin effect or temperature changes.

(4) SLIP

If the law of variation (or constancy) of the effective resistance is known, it can be used to find the slip at every point P on the current locus. We may now draw a further family of semicircles (or circular arcs) as in Fig. 5, this time with the centres on the vertical axis. These show the locus of the extremity of the current vector for various constant values of ${}_{pu}X$ and variable resistance. (The current-locus and ${}_{pu}X$ circles in Fig. 5

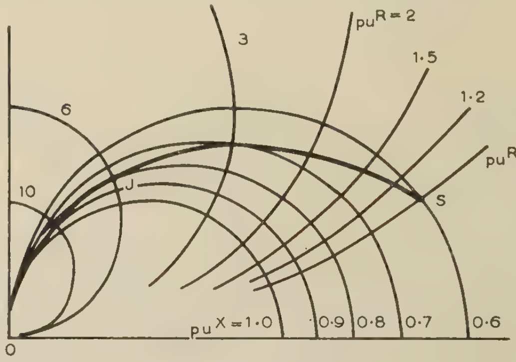

Fig. 5.—Current locus of induction motor with leakage-path saturation.

are the same as in Fig. 4.) The resistance circles in Fig. 5 are drawn for the particular values of per-unit resistance marked against each curve. Here

$${}_{pu}R = R_e/R_{e0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$R_e = R_1 + r_2/s \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$R_{e0} = R_1 + r_{20} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and r_{20} is the equivalent rotor resistance at standstill. Next, we may write

$$r_2 = mR_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where $m = m(s)$ for deep-bar or double-cage rotors and is approximately constant for plain squirrel-cage rotors. From eqns. (4)–(7),

$$R_e = R_1(1 + m/s) \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and

$$R_{e0} = R_1(1 + m_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

with

$$m_0 = r_{20}/R_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and hence

$${}_{pu}R = (1 + m/s)/(1 + m_0) \quad . \quad . \quad . \quad . \quad (11)$$

Fig. 6 shows the per-unit resistance varying with slip; curve (*a*) applies to a 'plain'-cage 25 h.p. 4-pole motor, assuming $m = 1{\cdot}5$ = constant; curve (*b*) is for a 25 h.p. 4-pole machine with deep-bar rotor conductors, for which $m = m(s)$ is given by curve (*c*) in Fig. 6. The per-unit resistance curves in Fig. 6 make it possible to determine the slip at every point on the current locus. Thus the slip at point J on the current-locus in Fig. 5 is governed by J lying on the ${}_{pu}R = 6$ circle; from Fig. 6, ${}_{pu}R = 6$ gives $s = 10{\cdot}5\%$ for the plain-cage motor, and $s = 8\%$ for the machine with deep-bar rotor construction.

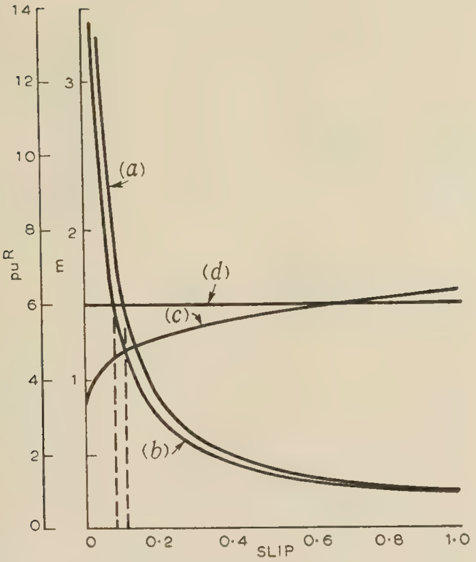

Fig. 6.—Variation of rotor/stator resistance ratio and total equivalent resistance (per unit) with slip.

(a) ${}_{pu}R$ for plain-cage rotor with $m = 1\cdot5 =$ constant.
(b) ${}_{pu}R$ for deep-bar rotor.
(c) $m = m(s)$ for deep-bar rotor.
(d) $m = 1\cdot5 =$ constant for plain-cage rotor.

(5) STARTING PERFORMANCE

The two families of circles shown in Fig. 5 can serve to present a useful physical picture of the influence of the circuit parameters on the starting performance. This includes machines with double-cage or deep-bar rotors, as well as those with simple cage construction. As an illustration, we may start at the point S_0 in Fig. 7: OS_0 is the starting current corresponding to

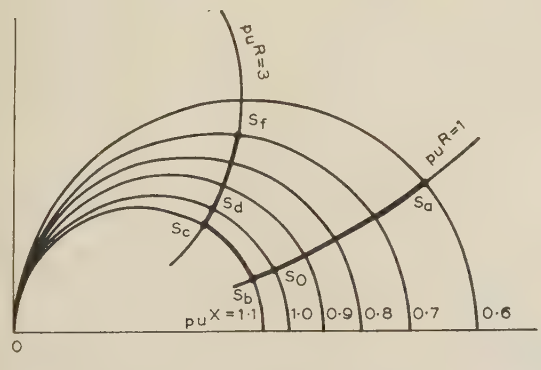

Fig. 7.—Movements of the starting-point, S, with parameter changes in 3-phase induction motors.

(a) S_0–S_a: plain-cage rotor.
(b) S_b–S_c–S_d–S_f: deep-bar or double-cage rotor.

${}_{pu}X = 1$ and ${}_{pu}R = 1$, i.e. assuming no saturation effects at starting and no skin effect in the rotor conductors at standstill. If a plain-cage rotor is used with insignificant skin effect but appreciable saturation at starting, the starting-point will move upwards along the ${}_{pu}R = 1$ circle to some position S_a. OS_a is the new starting current; it is clear that both its magnitude and power factor have increased as a result of saturation of the leakage paths.

In deep-bar or double-cage rotors we note first that the slot reactance at slip frequency is always higher than in plain-cage rotors. Hence the Heyland circle for running conditions must be smaller in diameter. For usual designs this decrease of diameter is of the order of 10%. Thus, in Fig. 7 the starting-point moves first from S_0 to S_b, the latter lying at the intersection of the ${}_{pu}X = 1\cdot1$ circle (say) and the ${}_{pu}R = 1$ circle. (${}_{pu}X = 1\cdot1$ for the plain-cage machine is here assumed to correspond to ${}_{pu}X = 1\cdot0$ for a rotor with deep-bar or double-cage construction.) Next, bearing in mind that the equivalent rotor resistance at standstill may be 2–3 times higher in such rotors than in the corresponding plain-cage machines, the starting-point will shift from S_b to S_c, at the intersection of the ${}_{pu}X = 1\cdot1$ and ${}_{pu}R = 3$ circles, say. Furthermore, owing to skin effect at line frequency, there is a reduction in the reactance of the rotor slots compared with the plain-cage machine; the starting-point will therefore move back from S_c along the ${}_{pu}R = 3$ circle to S_d, somewhere near its intersection with the ${}_{pu}X = 1$ circle.

Lastly, owing to saturation effects, the starting-point will once again be displaced upwards along this particular ${}_{pu}R$ circle, e.g. to S_f. The influence of each of these changes upon the magnitude and power factor of the starting current is very clearly shown by Fig. 7. In interpreting this Figure it is necessary to bear in mind that, for the sake of comparison, the line from S_0 to S_a characterizing a machine with a plain-cage rotor, and the line $S_bS_cS_dS_f$, representative of deep-bar or double-cage rotors within the same stator, possessing three times higher starting resistance, have been superimposed to form a composite diagram in which the calibration of the ${}_{pu}X$ circles is that for a plain-cage machine. It is interesting to observe also that the smaller Heyland circle for running conditions is responsible for the well-known fact that the power factor between no load and maximum load, together with the breakdown torque, are somewhat lower for double-cage rotors than in corresponding plain-cage machines.

(6) OUTPUT AND TORQUE LINES

(6.1) Resistances and Reactances Constant.

From the conventional circle diagram of an induction motor, e.g. as shown in Fig. 2, additional machine characteristics are usually derived by inserting the 'output line' OS and 'torque line' OK; both are straight lines, the position of the torque line being determined by the relationship

$$\frac{SK}{KM} = \frac{r_2}{R_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The linearity of the output line is based on the relationship

$$\frac{QN}{SM} = \frac{ON}{OM} = \frac{ON/OA}{OM/OA} = \frac{\frac{ON}{OP}\,\frac{OP}{OA}}{\frac{OM}{OS}\,\frac{OS}{OA}} = \frac{\left(\frac{OP}{OA}\right)^2}{\left(\frac{OS}{OA}\right)^2} = \frac{OP^2}{OS^2} = \frac{I^2}{I_s^2} \quad . \quad . \quad . \quad . \quad (13)$$

Thus, the resistance being constant and SM representing the copper losses when the standstill current I_s is flowing, QN will give the copper losses with a load current I of magnitude OP. Furthermore, since PN represents the input power, the intercept PQ is a measure of the output power at the point P on the current locus. Finally, by eqn. (12) and geometrical similarity, QT represents the rotor copper loss at a load current OP; hence the intercept PT is a measure of the rotor input power and therefore of the torque.

(6.2) Resistances and/or Reactances Variable

(6.2.1) Leakage Reactance varying with Current; Resistances Constant.

In Fig. 8 the current locus of Fig. 4 is redrawn together with three relevant ${}_{pu}X$ circles, those for rated current (${}_{pu}X = 1$), actual load current OP (${}_{pu}X_p$) and standstill current (${}_{pu}X_s$).

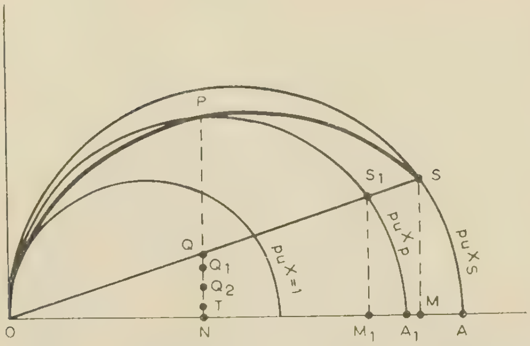

Fig. 8.—Current locus of induction motor with leakage-path saturation.

However, the straight line OS, on which Q lies, is not the output line as in the previous case, for now the variation of leakage reactances results in QN being no longer proportional to the copper loss at the point P. To construct the new output line we may start by establishing the following relationships for Fig. 8:

From eqn. (13)
$$\frac{QN}{S_1M_1} = \frac{OP^2}{OS_1^2} \qquad (14)$$

Hence
$$\frac{QN}{SM} = \frac{QN}{S_1M_1}\frac{S_1M_1}{SM} = \frac{OP^2}{OS_1^2}\frac{OS_1}{OS} = \frac{OP^2}{OS^2}\frac{OS}{OS_1} \qquad (15)$$

But since the diameters of the ${}_{pu}X$ circles are inversely proportional to the corresponding reactances,

$$\frac{OS}{OS_1} = \frac{OA}{OA_1} = \frac{{}_{pu}X_p}{{}_{pu}X_s} \qquad (16)$$

Hence, if a point Q_1 is found between Q and N such that

$$\frac{Q_1N}{QN} = \frac{{}_{pu}X_s}{{}_{pu}X_p} \qquad (17)$$

then, from eqns. (15)–(17)

$$\frac{Q_1N}{SM} = \frac{Q_1N}{QN}\frac{QN}{SM} = \frac{OP^2}{OS^2} \qquad (18)$$

The copper losses for constant rotor resistance and a load current OP are therefore given by the intercept Q_1N. Hence the appropriate output line for plain-cage induction motors can be constructed by locating Q_1 so that it satisfies eqn. (17) and repeating this process for a number of points P along the current locus. The torque line is obtained in this case by dividing the intercept Q_1N in the ratio r_2 to R_1, i.e. as for a conventional circle diagram, except that the torque line will no longer be straight.

(6.2.2) Leakage Reactance varying with Current; Rotor Resistance varying with Slip.

If the rotor resistance is variable, e.g. owing to skin effect, a further modification of the copper losses takes place; this will be reflected in the shape of the output line. If the manner of rotor-resistance variation with slip is known, e.g. in graphical form, such as in Fig. 6, a new point, Q_2, may be located in Fig. 8 on the vertical line through P such that

$$\frac{Q_2N}{Q_1N} = u = \frac{R_1 + r_2}{R_1 + r_{20}} = \frac{1+m}{1+m_0} \qquad (19)$$

Q_2N then represents the copper loss for a load current OP. Fig. 9 shows the variation of the output parameter u with slip

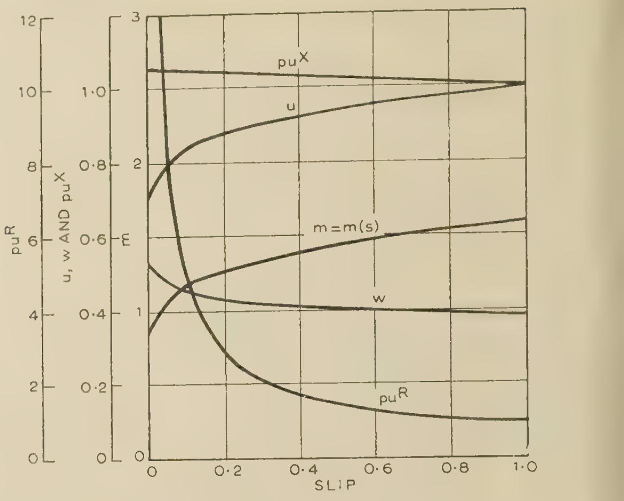

Fig. 9.—Variation of the output and torque parameters, and per-unit reactance, with slip.

for $m = m(s)$ as given in Fig. 6 (and redrawn in Fig. 9 for convenience). As was shown earlier, the slip at each point P on the current locus can be determined from the data in Fig. 6; hence Fig. 9 enables us to locate Q_2 for a series of points along the current locus, and so obtain the output line for induction motors with deep-bar or double-cage rotors. Fig. 10 shows this curve for a 25 h.p. 4-pole machine with deep-bar rotor construction.

To obtain the torque line for such machines we must locate the point T in such a way that

$$\frac{TN}{Q_2N} = w = \frac{R_1}{R_1 + r_2} = \frac{1}{1+m} \qquad (20)$$

i.e. divide the intercept Q_2N, representing the total copper loss, in the ratio of the stator and rotor resistance at the appropriate slip. The curve of the torque parameter, w, against slip is also shown in Fig. 9 for the function $m = m(s)$ in the same diagram. This is then used to construct the torque line in Fig. 10.

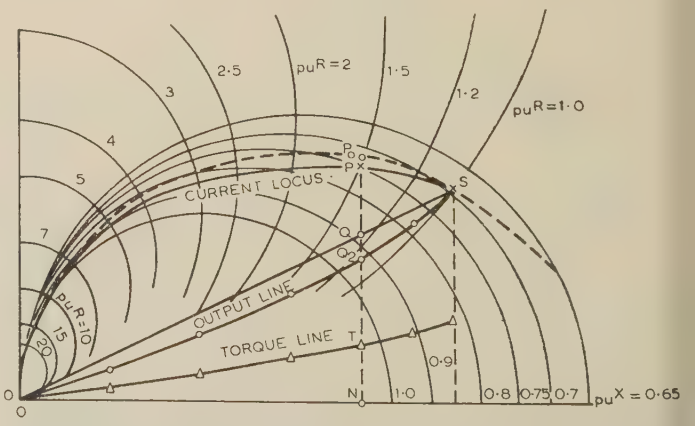

Fig. 10.—Complete performance chart (locus diagram) of 25 h.p. 3-phase, 4-pole induction motor with deep-bar rotor construction.

(6.2.3) Leakage Reactance varying with Slip as well as Current; Rotor Resistance varying with Slip.

In double-cage and deep-bar rotors the leakage reactance varies, not only with the current, but also with the slip. This is due to the redistribution of the current filaments as the rotor frequency changes during starting. The change of total leakage

reactance is not great, however, in motors of conventional design. To deal with this problem it is therefore assumed that the variation of $_{pu}X$ with slip is linear and is the same for all constant values of current.

The estimated variation of $_{pu}X$ with slip for the 25 h.p. motor used in our illustrative example is shown in Fig. 9. This is then used to construct the true locus for this machine. The broken curve in Fig. 10 is drawn first. It represents the current locus assuming $_{pu}X$ to be independent of the slip; the construction is thus described in Section 3. Next, taking a point P_0 on this curve, where $_{pu}R = 1 \cdot 5$, we note from Fig. 9 that, for this value of $_{pu}R$, $s = 0 \cdot 5$ and that $_{pu}X$ is some 3% higher at this slip than at standstill. We therefore move inwards along the $_{pu}R = 1 \cdot 5$ circle from P_0, where $_{pu}X = 0 \cdot 72$, to the point P where $_{pu}X$ is about $0 \cdot 745$ (this actually includes some allowance for the slight decrease of current as we move from P_0 to P). On repeating this construction at a number of points, the current locus in Fig. 10 is rapidly obtained.* The output and torque lines may then be constructed as described in Section 6.2.2.

(7) PERFORMANCE CURVES

From the current locus in Fig. 10, together with the output and torque lines in the same Figure, we can derive the per-

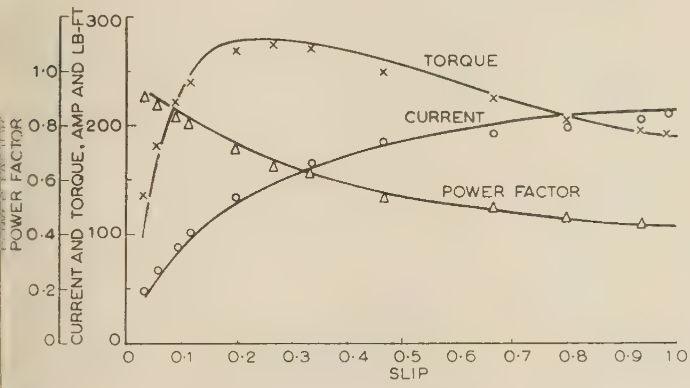

Fig. 11.—Performance curves of 25 h.p. 3-phase 4-pole induction motor with deep-bar rotor construction.

Note.—The curves were derived from the locus diagram in Fig. 10, while the points shown are based on the results of a comprehensive load test.

formance curves shown in Fig. 11. The method of doing this is quite conventional and need not be repeated here. Fig. 11 also shows points obtained by performing a load test on the 25 h.p. induction motor with deep-bar rotor construction to which these diagrams apply. The agreement between the calculated and measured values may be taken as a measure of the reliability of the method described in the paper. The chief sources of error are the difficulties associated with the estimation of leakage reactances[7] and to a smaller extent the lack of precise information regarding resistance variation due to skin effect and temperature changes. Thus, while the discrepancies between measured and calculated values may seem large, they are nevertheless well within the usual tolerances encountered in this type of work.[5]

* The no-load current has been neglected in drawing the current locus in Fig. 10.

(8) CONCLUSION

A method has been described which restores much of the usefulness of the locus-diagram approach to induction-motor studies. Although the statements made in the paper refer to squirrel-cage motors throughout, the techniques described can be applied to wound-rotor machines with minor modifications only. The essential simplicity of the original circle diagram may be lost, but the clarity of insight gained into the influence of parameter changes on machine performance is not impaired. The accuracy of the techniques introduced is much greater than that of the data on which they are based.

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APPLICATION OF A VARIABLE-REACTOR/CAPACITOR COMBINATION FOR REVERSING AND CONTROLLING THE SPEED OF POLYPHASE INDUCTION MOTORS

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SUMMARY

By introducing a variable reactor paralleled with a fixed capacitor in one of the supply lines of a 3-phase induction motor, the speed and direction of rotation can be controlled, by controlling the value of the the external effective reactance. Applying the method of symmetrical components, both the starting and running performances of such a motor are analysed. If the external reactance is made to vary automatically with speed, this gives a method of controlling, and reversing with dynamic braking, the speed of the motor.

LIST OF SYMBOLS

$V, V\angle 240°, V\angle 120°$ = Line voltages.
I_1, I_2, I_3 = Line currents.
I_a, I_b, I_c = Phase currents.
V_p = Positive-sequence component of the voltages applied to the windings.
V_n = Negative-sequence component of the voltages applied to the windings.
I_p = Positive-sequence component of the stator phase currents.
I_{2p} = Positive-sequence component of the rotor phase currents.
I_n = Negative-sequence component of the stator phase currents.
I_{2n} = Negative-sequence component of the rotor phase currents.
Z_p = Impedance of the motor per phase to positive-sequence currents.
Z_n = Impedance of the motor per phase to negative-sequence currents.
$Z_1 = R_1 + jX_1$ = Leakage impedance of the stator per phase.
$Z_2 = R_2 + jX_2$ = Leakage impedance of the rotor per per phase at standstill.
$Z_s = R_s + jX_s$ = Impedance of the motor per phase at standstill.
Z_m = Magnetizing impedance of the motor per phase.
$Z_e = jX_e$ = Single-phase external impedance (the resistance component is usually neglected).

(1) BASIC IDEAS

The Kusa method of starting, introducing a single-phase reactor in one of the 3-phase supply lines, for controlling the acceleration and reducing the starting apparent power of 3-phase squirrel-cage induction motors is fairly well known, even though it is not widely used. If the external single-phase reactance is kept permanently in circuit, various speed/torque characteristics are obtained for the same induction motor, depending upon the value of the reactance (Fig. 1). In the construction of these characteristics, the value of the reactance is assumed to remain constant throughout the full range of operation of the motor, which will obviously not be the case if, as is usual, an iron-core reactor is used. If, depending upon the speed of the motor, the reactance can be made to vary automatically as shown in curve 3, a variable speed/torque characteristic, as shown by curve 2, is obtained for the machine. This automatic control of the reactance can be achieved by using a saturable reactor with a d.c. control winding (Fig. 2). The current in the control winding is automatically varied by the d.c. tachometer generator and a reference direct voltage V_d. If the load torque increases, the machine slows down, the control current increases, the reactance decreases, the motor builds up a larger torque and thus the increased load torque is met with a decrease in speed. The steepness of the speed/torque characteristic will depend on the normal characteristic of the motor and the design of the reactor and control circuit.

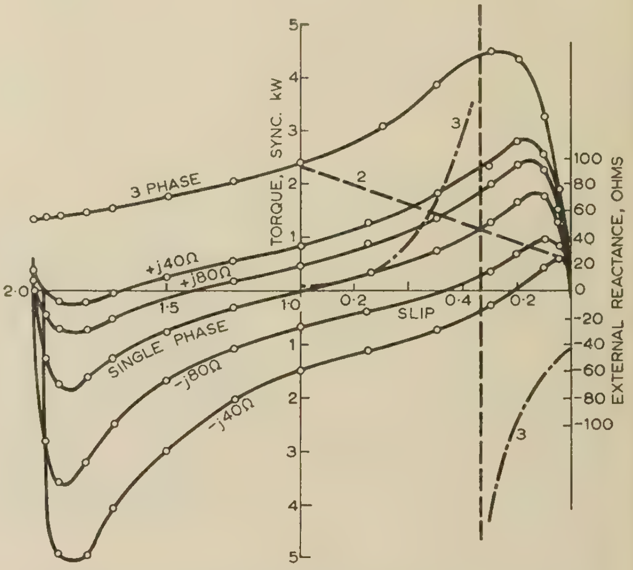

Fig. 1.—Speed/torque and speed/reactance curves.

—— Speed/torque characteristics.
---- Required speed/torque characteristic.
—·— Speed/reactance curve.

By using a capacitor in parallel with the variable reactor the range of variation of the external reactance is increased and its sign also can be reversed. This makes it possible to reverse the direction of rotation of the motor without interrupting the main circuit.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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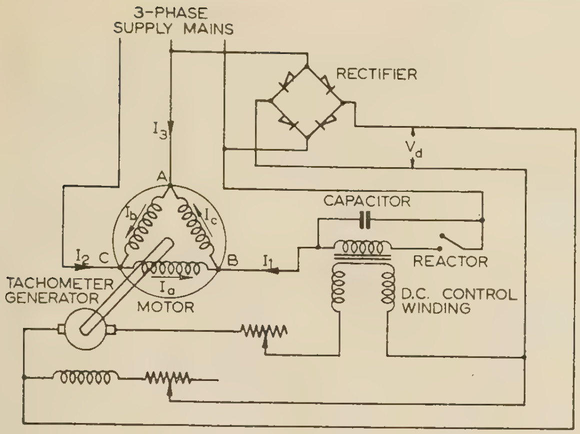

Fig. 2.—Circuit arrangement.

(2) CURRENT AND TORQUE EQUATIONS

For a delta-connected motor (Fig. 2), applying the method of symmetrical components, the following equations are derived:

$$V_{AC} = V;\ V_{BA} = V\angle 240^\circ - I_1 Z_e;\ V_{CB} = V\angle 120^\circ + I_1 Z_e$$

$$V_p = \tfrac{1}{3}[V + (V\angle 240^\circ - I_1 Z_e)\angle 120^\circ + (V\angle 120^\circ + I_1 Z_e)\angle 240^\circ]$$

$$= V + \frac{I_1 Z_e \diagup 90^\circ}{\sqrt{3}} \ldots$$

Similarly, $V_n = \dfrac{I_1 Z_e \angle 90^\circ}{\sqrt{3}} \ldots$

$$I_n = \frac{V_n}{Z_n} = \frac{I_1 Z_e \angle 90^\circ}{(\sqrt{3}) Z_n} \quad \ldots \quad (1)$$

$$I_p = \frac{V_p}{Z_p} = \frac{V + I_1 Z_e \diagup 90^\circ / \sqrt{3}}{Z_p} \quad \ldots \quad (2)$$

$$I_b = I_p + I_n;\ I_c = I_p\angle 240^\circ + I_n\angle 120^\circ;\ I_a = I_p\angle 120^\circ + I_n\angle 240^\circ$$

$$I_1 = I_c - I_a = I_p\angle 240^\circ + I_n\angle 120^\circ - I_p\angle 120^\circ - I_n\angle 240^\circ$$

$$= \sqrt{3}(I_p \diagup 90^\circ + I_n\angle 90^\circ) \quad \ldots \quad (3)$$

Substituting eqn. (3) in eqns. (1) and (2) and solving,

$$I_p = \frac{V(Z_n + Z_e)}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (4)$$

$$I_n = \frac{V Z_e}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (5)$$

$$I_b = \frac{V(Z_n + 2Z_e)}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (6)$$

$$I_c = \frac{V(Z_n + Z_e \diagup 60^\circ)\angle 240^\circ}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (7)$$

$$I_a = \frac{V(Z_n + Z_e\angle 60^\circ)\angle 120^\circ}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (8)$$

$$I_1 = \frac{(\sqrt{3}) V Z_n \angle 270^\circ}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (9)$$

$$I_2 = \frac{(\sqrt{3}) V[Z_n\angle 150^\circ - (\sqrt{3}) Z_e]}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (10)$$

$$I_3 = \frac{(\sqrt{3}) V[Z_n\angle 30^\circ + (\sqrt{3}) Z_e]}{Z_p Z_n + Z_n Z_e + Z_e Z_p} \quad \ldots \quad (11)$$

$$I_{2p} = I_p \frac{Z_m}{Z_m + \dfrac{R_2}{S} + jX_2} \quad \ldots \quad (12)$$

$$I_{2n} = I_n \frac{Z_m}{Z_m + \dfrac{R_2}{2 - S} + JX_2} \quad \ldots \quad (13)$$

Hence torque in synchronous watts at any slip S is given by

$$3I_{2p}^2 \frac{R_2}{S} - 3I_{2n}^2 \frac{R_2}{2 - S} \quad \ldots \quad (14)$$

It is assumed, for the sake of simplicity, that the rotor resistance for negative-sequence conditions is the same as that for positive-sequence conditions.

The following graphical construction for I_p, I_n, torque, input and output in terms of the corresponding quantities, when there is no external reactance, may also be adopted.

Instead of the impedances Z_p, Z_n, Z_e introducing the corresponding admittances Y_p, Y_n, Y_e,

$$I_p = V Y_p \frac{Y_e + Y_n}{2\left(\dfrac{Y_e}{2} + \dfrac{Y_p + Y_n}{2}\right)}$$

$$I_n = V Y_n \frac{Y_p}{2\left(\dfrac{Y_e}{2} + \dfrac{Y_p + Y_n}{2}\right)}$$

Fig. 3 shows the circle diagram of the motor when the applied voltages are balanced and equal. Marked on this circle K are the standstill point S, the infinite point and M the centre of the circle. A circle K′ drawn through these points is the locus of the current $V(Y_p + Y_n)/2$. M′ is the centre of this circle. Point D lies on its circumference and is obtained by producing MM′. The points VY_p and $V(Y_p + Y_n)/2$ lie on a line through the point D. B and C represent the points $-VY_e$ and $-VY_e/2$. Then, for any value of slip for which point E will hold good for the motor under balanced conditions, with the introduction of the external single-phase impedance Z_e,

$$I_p = \mathrm{OE}\frac{\mathrm{GB}}{2d};\quad I_n = \mathrm{OG}\frac{\mathrm{OE}}{2d}$$

Torque per phase $= \mathrm{EF}(\mathrm{GB}/2d)^2 - \mathrm{GQ}(\mathrm{OE}/2d)^2$

Output per phase $= \mathrm{EJ}(\mathrm{GB}/2d)^2 - \mathrm{GP}(\mathrm{OE}/2d)^2$

(3) STARTING CHARACTERISTICS

On starting, $Z_p = Z_n = Z_s$; substituting these values in the current equations,

$$I_p = \frac{V(Z_s + Z_e)}{Z_s(Z_s + 2Z_e)} \quad \ldots \quad (15)$$

$$I_n = \frac{V Z_e}{Z_s(Z_s + 2Z_e)} \quad \ldots \quad (16)$$

$$I_b = \frac{V}{Z_s}$$

$$I_c = \frac{V(Z_s\angle 240^\circ - Z_e)}{Z_s(Z_s + 2Z_e)} = [I_b - (\sqrt{3}) I_n\angle 30^\circ]\angle 240^\circ$$

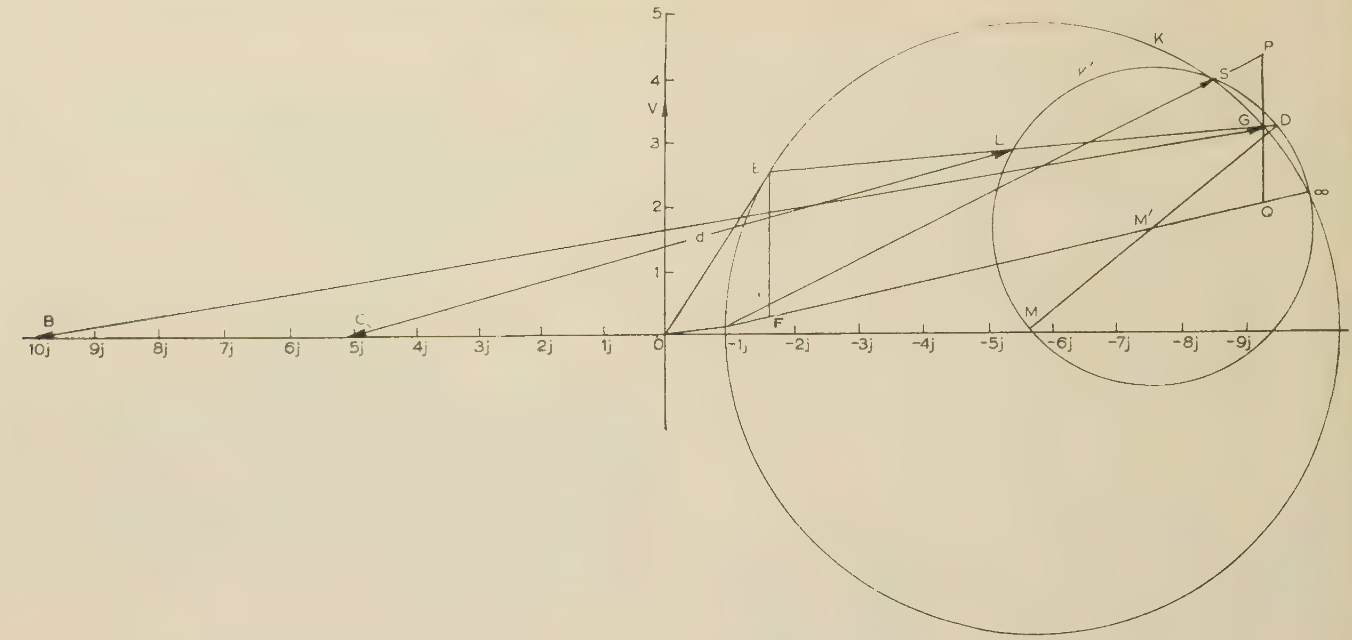

Fig. 3.—Graphical construction for I_p, I_n and speed/torque characteristic.

$$I_a = \frac{V(Z_s\angle 120^\circ - Z_e)}{Z_s(Z_s + 2Z_e)} = [I_b - (\sqrt{3})I_n\angle 30^\circ]\angle 120^\circ$$

$$I_1 = \frac{(\sqrt{3})V\angle 270^\circ}{Z_s + 2Z_e} = \sqrt{3}(I_b - 2I_n)\angle 90^\circ$$

$$I_2 = \frac{(\sqrt{3})V[Z_s\angle 150^\circ - (\sqrt{3})Z_e]}{Z_s(Z_s + 2Z_e)} = \sqrt{3}(I_b - I_n\angle 60^\circ)\angle 150^\circ$$

$$I_3 = \frac{(\sqrt{3})V[Z_s\angle 30^\circ + (\sqrt{3})Z_e]}{Z_s(Z_s + 2Z_e)} = \sqrt{3}(I_b - I_n\angle 60^\circ)\angle 30^\circ$$

Fig. 4 gives the loci of these current vectors as the value of Z_e is changed, neglecting its resistance. These are all circles except that of I_b, which remains constant. The loci of I_c, I_a, I_1, I_2 and I_3 are easily derived from those of I_b and I_n. The same circle can serve as the locus of I_p and I_n, OP representing I_p and PS, I_n.

$$\text{Starting torque} = R_2(I_p^2 - I_n^2)\left(\frac{Z_m}{Z_m + Z_2}\right)^2 \text{synchronous watts}$$

per phase. Considering any point P on the locus diagram of I_p and I_n,

$$I_p^2 - I_n^2 = \text{OP}^2 - \text{PS}^2 = \text{OX}^2 - \text{XS}^2$$

$$= (\text{OX} + \text{XS})(\text{OO}' + \text{O}'\text{X} - \text{O}'\text{S} + \text{O}'\text{X}) = 2\frac{V}{Z_s}\text{O}'\text{X}$$

where O′ is the mid-point of OS and PX is perpendicular to OS.

$$\text{Therefore starting torque} = \frac{6VR_2}{Z_s}\left(\frac{Z_m}{Z_m + Z_2}\right)^2 \text{O}'\text{X}$$

and is therefore proportional to O′X.

Starting with $Z_e = \infty$ (one line open, single-phase operation, point O′), as Z_e is decreased, the starting torque increases from O to O′S the value corresponding to balanced operation ($Z_e = 0$). Then if Z_e is made negative by using a capacitor, starting torques higher than O′S are obtained. Maximum torque is obtained when the point M is reached, and it can be shown that this is equal to $(Z_s + R_s/2R_s)$O′S. As the capacitive reactance is further increased the torque decreases, and at R it is equal to O′S, the capacitive reactance required being equal to half the short-circuit reactance of the machine. At T(O′T is perpendicular to OS) the torque is zero and the capacitive reactance is $R_s^2/2X_s + X_s^2/Z_s$. When the capacitive reactance is further increased the torque becomes negative, i.e. the machine will start in the reverse direction. The region TM′O′ is then traversed, the torque increasing in the negative direction until point M′ is reached. At M′ the negative torque is a maximum and is equal to $(Z_s - R_s/2R_s)$O′S. Below M′ the negative torque decreases and is finally reduced to zero when point O′ is reached.

With normal integral-horse-power motors the capacitors required to obtain either the maximum positive torque or the maximum negative torque would have to be very large, particularly the former, so that it is not practicable to adopt this method for obtaining higher starting torques.

For the purposes of calculations and tests, a normal commercial 3 h.p. 400-volt 50 c/s 1 440 r.p.m. 3-phase delta-connected squirrel-cage motor, which was available, was chosen; it had the following measured constants:

$$Z_m = 35 + j418; \; Z_1 = 8{\cdot}28 + j20; \; Z_2 = 10{\cdot}1 + j20$$

Fig. 5 illustrates the variation of the starting torque as Z_e is varied.

(4) OPERATION AT SYNCHRONOUS SPEED

Fig. 6 shows the circle diagrams of I_p and I_n when the machine is driven at synchronous speed, for different values of Z_e. The range of variation of I_p is very much smaller than that of I_n.

(5) RUNNING CHARACTERISTICS

Fig. 1 shows the speed/torque characteristics; Fig. 7, input versus speed; and Fig. 8, efficiency versus speed for various values of the external impedance. The input curves illustrate how the power input is reduced by this method when the machine

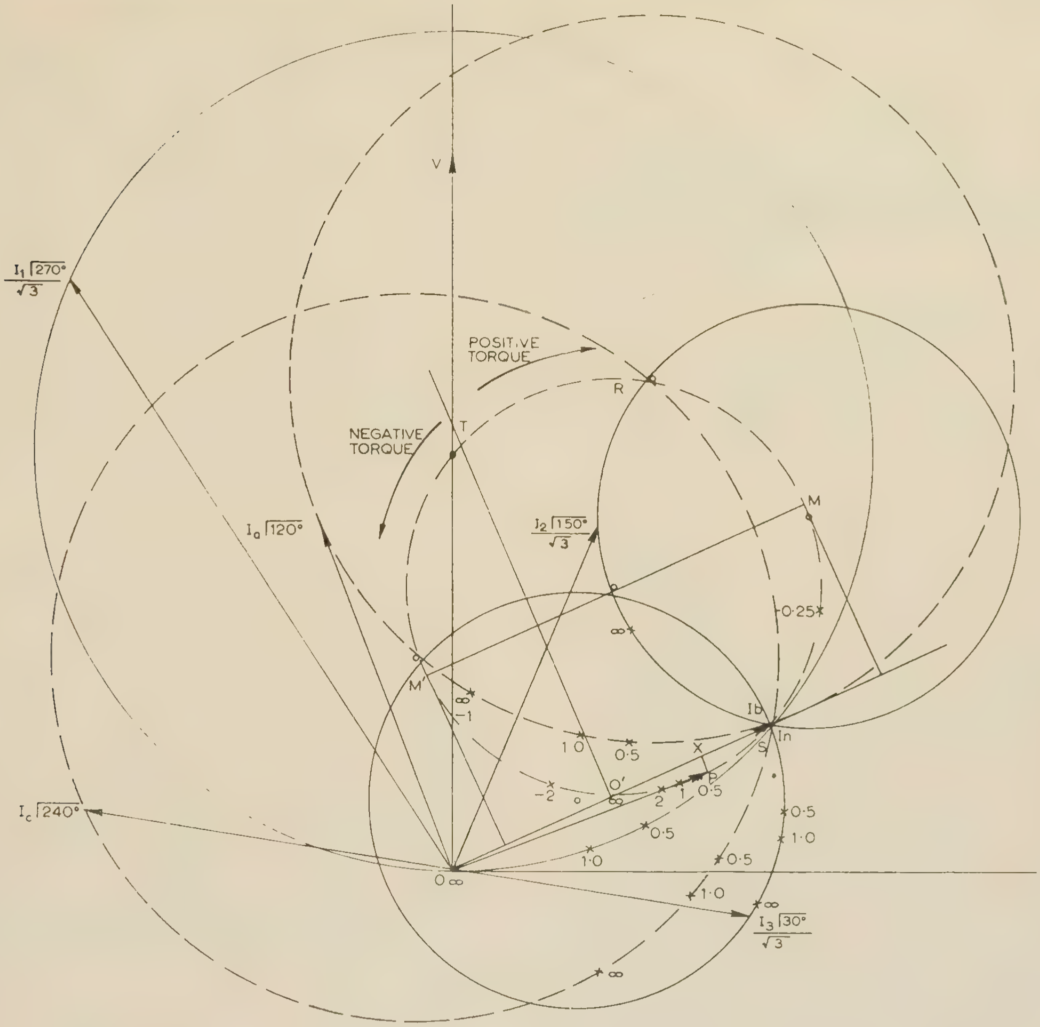

Fig. 4.—Starting-current circle diagrams.

Starting currents versus X_e.
Numbers indicate X_e/X_s.

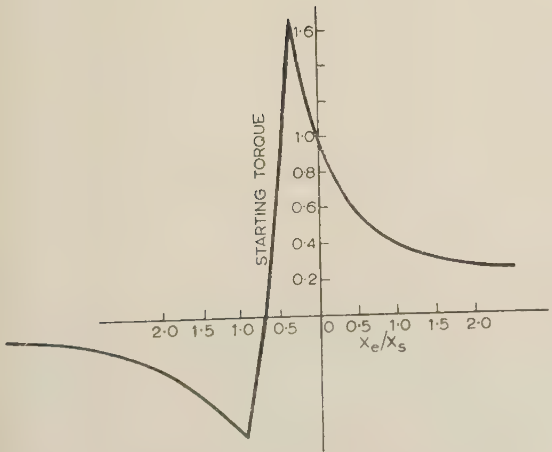

Fig. 5.—Starting torque versus external reactance.

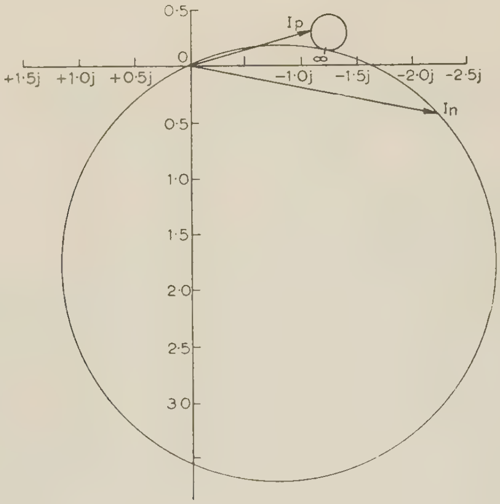

Fig. 6.—Operation at synchronous speed.

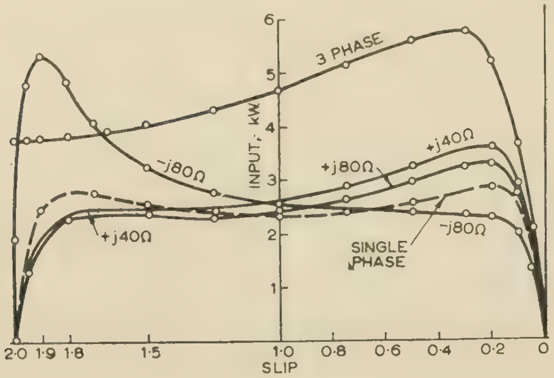

Fig. 7.—Input/slip curves.

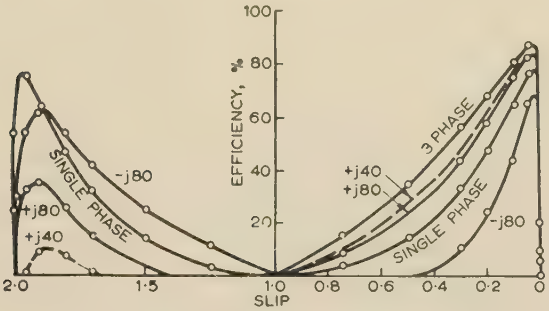

Fig. 8.—Efficiency/slip curves.

has to operate at low speeds developing low torques. Considerable torque can be developed in the reverse direction by the use of a reasonable capacitor, even though the starting torque in such a case would be very low.

Even with capacitive reactance, positive torque is developed at high speeds, and hence, unless the load torque is sufficiently high, the motor will not decelerate if the reactor is open-circuited and only the capacitor is left in circuit. But below a certain speed, which depends upon the value of the capacitive reactance, the machine will develop torque in the reverse direction and will slow down, come to rest and start in the reverse direction, if the starting torque developed is sufficiently high.

(6) EXPERIMENTAL RESULTS

As a normal induction motor was used, and as it was difficult to set up a suitable variable reactor of wide range with the accompanying control circuit of quick response, it was not possible to obtain satisfactory experimental results. But the experiments showed that the method is quite practicable and that very good results can be obtained with high-torque and double-squirrel-cage motors.

Fig. 9 shows the speed/torque characteristics of the machine as calculated, and as obtained experimentally by applying a reduced voltage and then increasing the measured torque as the square of the voltage. An air-core reactor was used. It is seen that at high speeds the agreement between the calculated and experimental values is fairly close, but at low speeds, with balanced operation, the observed values are higher than the calculated values, and with unbalanced operation due to the reactor, the observed values are lower than the calculated values. Fig. 10 also gives the speed/torque characteristics for the three cases. The motor was direct coupled to a separately excited d.c. generator. The armature circuit of the generator was closed through a low-resistance high-capacitive-reactance circuit. During the accelerating period the voltage drop across the resistance is approximately proportional to the torque, and the generated direct voltage is proportional to the speed. The armature direct voltage was applied to the X-plates, and the voltage drop across the resistance to the Y-plates, of a cathode-ray oscilloscope.

Fig. 11 shows the current and speed variation during one

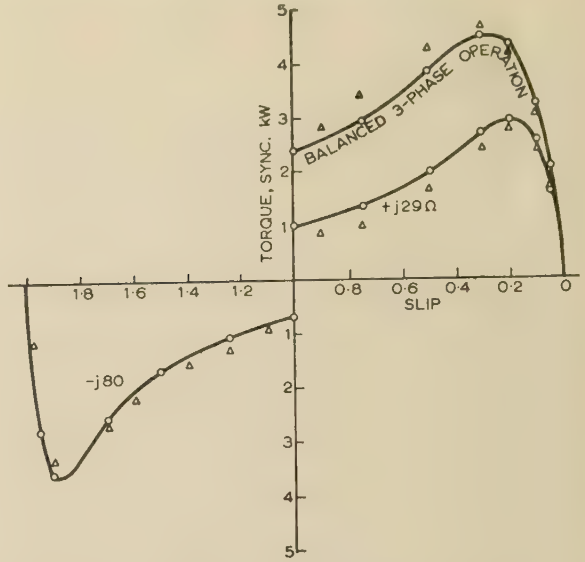

Fig. 9.—Experimental speed/torque characteristics.

○ Calculated points.
△ Experimental points.

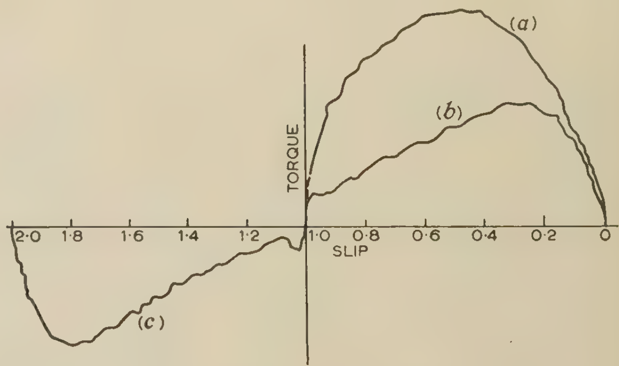

Fig. 10.—Speed/torque oscillograms.

(*a*) Balanced 3-phase operation.
(*b*) With 29-ohm inductive reactance.
(*c*) With 80-ohm capacitive reactance.

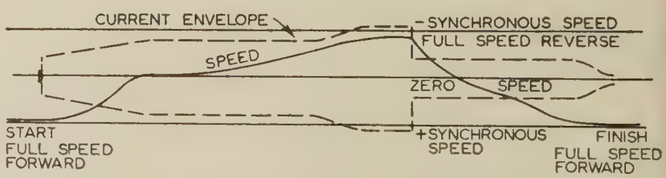

Fig. 11.—Oscillogram showing current and speed variation during one cycle of operation.

Time scale reduced; speed and current scales increased.

complete cycle of operation. When the motor is running on load at a certain speed, with both the reactor and capacitor in circuit, the reactor is cut off. The motor decelerates, comes to rest, reverses and gradually attains full speed in the reverse direction. Now the reactor is reintroduced, the motor decelerates, comes to rest, accelerates and attains the initial speed. The motor was direct coupled to a separately excited d.c. machine. The oscillogram of the d.c. armature terminal voltage indicates approximately the speed variation.

(7) CONCLUSIONS

Experiments indicate that it is possible to obtain a 'soft characteristic' with squirrel-cage induction motors with an automatically controlled saturable reactor paralleled with a capacitor, which has been shown to be theoretically feasible. The capacitor is necessary, to reverse the direction of rotation. Dynamic braking is possible without any extra equipment. High-torque or double-cage motors should be preferred, and the reactor with its control circuit has to be properly designed to ensure stable operation.

(8) ACKNOWLEDGMENTS

I thank Mr. Thomas Philip and Mr. E. M. Gopal of the Indian Institute of Technology, Kharagpur, for their assistance in taking the oscillograms, and Mr. Namananda Das, a student, for carrying out some of the calculations.

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DISCUSSION ON 'EARTH ELECTRODE SYSTEMS FOR LARGE ELECTRIC POWER STATIONS'*

Before the East Midland Centre *at* Nottingham *7th January, and the* Western Supply Group *at* Cardiff *20th January*, 1958.

Mr. W. W. Smith (*at Nottingham*): In 1954, just prior to the commissioning of Drakelow power station in the East Midlands Division, we took the opportunity of subjecting the earth-plate system of the adjacent 132 kV substation to 50 c/s and d.c. tests of 200 amp approximately. The primary object was to explore the path taken by earth currents returning from a carefully arranged fault one mile away from the site, and to see whether the actual total resistance of the 132 kV earth-plate system differed in any way from the measurements taken with light currents. Potential-gradient curves were plotted for each of seven directions, ranging from parallel to the faulty overhead line, passing through a direction perpendicular to the line, and finishing in the completely opposite direction. Measurements were taken with a valve voltmeter connected between the earth plate at the feeding point and potential spikes driven about 9 in into the soil. Periodically oscillographic records were made of these voltages in relation to the injected line current.

After analysis of all the results obtained, the following general conclusions were drawn:

(*a*) Although the elaborate power-station earthing system was bonded to the 132 kV substation by cable sheaths with resistances of less than 0·02 ohm, it took no part in sharing the 50 c/s earth current.

(*b*) More than 54% of the 50 c/s earth-fault current returned to the earthing system via the main 132 kV structures, and very little via the substation earthing plates.

(*c*) The path taken by the current from the remote fault to the source was almost a mirror image of the outgoing path.

(*d*) If the voltage spike was driven in at a point perpendicular to the outgoing overhead line and about 100 ft away from it, the voltage induced in the connecting loop by the fault current in the overhead line was eliminated, and the resulting impedance measurement was found to agree exactly with that obtained by an earth-insulation tester under similar conditions.

(*e*) The impedance of the earth system at 50 c/s was 0·18 ohm, its resistance 0·15 ohm and its reactance 0·098 ohm, whereas the resistance at the same value of direct current, 200 amp, was 0·06 ohm.

(*f*) The effect of employing heavier currents at 50 c/s revealed the existence of non-linearities in the ground adjacent to the earth-electrode system, since an inspection of the current waveform showed pronounced harmonics near the crest value.

(*g*) If any earthed cable sheath happened to lie along the path of the returning earth-fault current, it acted as a far better collecting system for this current than electrodes placed on either side of it.

The conclusion is that care should be taken to see that cables with earthed sheaths enter at right angles to any possible returning earth-fault current.

Mr. G. P. Hutchinson (*at Cardiff*): I agree that a part of the design work is to some extent empirical and, it would seem, must remain so, since soils are far from homogeneous in any one place or depth. Soil-resistivity tests, however, if properly conducted, can give a fairly representative picture of the area and enable a reasonable first approximation to be made of the type of electrode system to be employed. The importance of this survey cannot be stressed too greatly, since it is the only yardstick by which to assess the requirements for a particular design, and I would have preferred the author to enlarge on this and to refer in detail to some of the methods and types of survey which can be employed. This point is borne out by reference to Fig. D, which shows soil-resistivity tests of two substation sites in South Wales, where the resistivities were measured, not only over the area of the site, but also at varying depths.

From Fig. D(i) it is obvious that a clear case exists for employing electrodes vertically driven to about 20 ft, where advantage can be taken of the low resistivities of the strata below 10 ft. Fig. D(ii) shows the opposite characteristic and indicates that no advantage could be taken of vertical electrodes. It is, in fact, a case for a horizontal conductor system laid a foot or two below the surface.

The two main criteria in the design of a suitable system are:

(*a*) To obtain as wide a distribution as possible of the electrode system within the substation site and to ensure efficient bonding of all 'earthy' metal to a main earth busbar system and to the electrode. This also includes cable sheaths and earth wires via the steelwork of the terminal towers.

(*b*) To strive within economic limits for total resistances which for the most onerous earth-fault condition will keep potentials within the 430-volt G.P.O. criterion.

* Humphries, J. D.: *Proceedings I.E.E.*, Paper No. 2341 S, March, 1957 (see 104 A, p. 383).

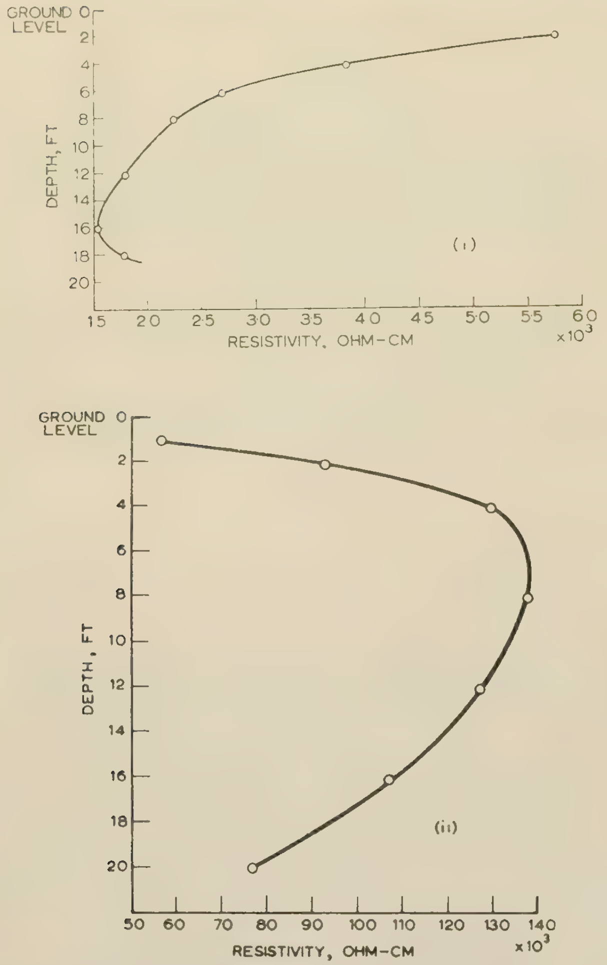

Fig. D.—Variation of resistivity with depth.

(i) At No. 5 Substation.
(ii) At No. 4 Substation.

The assessment of earth-fault currents in the calculation of (*b*), however, is often more difficult than would at first appear, since the tendency for earth currents to cluster in the vicinity of the conductor carrying the bulk of the current to the fault makes a theoretical prediction of the 'return' current distribution almost impossible. It is often considered that the most onerous condition is that of a fault to earth immediately outside the substation boundary, where all infeeds concentrate into the ground and return via the effective resistance of the electrode system. This could give a calculated potential rise far higher than would occur in practice, since, provided that earth-wire bonds were intact, the clustering phenomenon could cause 30–60% of the total current to return along the metallic connections, leaving only the balance to return via the electrode system. I feel that scope exists here for further researches to be made; the electrolytic tank could probably be used with good effect and more economic designs made possible.

No mention has been made of electrodes to deal specifically with lightning surges and to provide the earthing point for surge diverters and lightning conductors. I feel that this is a subject worthy of some attention, since surge diverters and lightning conductors form part of a station installation. It would appear that the most satisfactory arrangement is to make connections as direct and straight as possible and for the electrode itself to take the form of a 'radial counterpoise', in an attempt to limit the surge impedance to a value commensurate with the d.c. dissipation resistance.

Finally, has the author any knowledge of a low-resistivity clay which has quite recently appeared and is available for use on earthing systems? It is alleged to have a resistivity of the order 15–50 ohm-cm and a moisture content of about 20% after being in the ground for some time. Tests carried out with this clay have shown practically no seasonal variation of resistance over a 6-month trial period. It would seem that, if available at an economic cost, it could furnish a satisfactory substitute for the conventional coke surround which is used in high-resistivity soils when it is desired to increase the effective area of the metallic electrode.

Mr. K. G. Glover (*at Cardiff*): Has the author considered whether it may not be possible for stations to be too efficiently earthed? Apart from the economic aspect (that any conductor buried in the ground for earthing purposes means so much less of the total copper in the power system being available for carrying load current), the lower the resistance of the earth electrode system, the more earth-fault current will tend to flow via the earth itself rather than via the earth conductors. May not this be a bad tendency? If all items of plant and all stations are bonded together by an efficient low-resistance earth conductor, earth-fault currents will tend to flow along this route, and the main function of the earth electrode system will be to discharge static charges safely. This probably explains why the old earth-plate electrode system, inefficient though it often was, proved satisfactory in conjunction with a continuous earth conductor joining together all substations. Under these conditions, a high calculated value of earth-fault current will not necessarily mean high currents flowing through the ground.

This point has been touched on in Section 4 of the paper, but the argument that the necessity for efficient and costly earth electrodes is thereby reduced is not mentioned by the author.

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BRIDGE METHODS FOR DETERMINING SYMMETRICAL COMPONENTS OF CURRENT, VOLTAGE AND POWER, WITH SPECIAL REFERENCE TO ELECTRICAL MACHINERY

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SUMMARY

The isolation and separate measurement of symmetrical-component quantities is a logical corollary to the theoretical principles employed in the analysis of unbalanced polyphase systems. The paper provides a comprehensive account of the design, construction and adjustment of bridge networks which reduce to a routine procedure the measurement of sequence components of current, voltage and power in 3-phase and 2-phase systems. The bridges are designed for use with instrument transformers, and the significance of frequency variations and meter impedances are discussed. Examples of a few practical applications are included.

(1) INTRODUCTION

There is some excuse for the view that the solution of a problem in symmetrical-component terms is often complete except for the answer, for it can be a tedious task, especially in relation to machine problems, to extract numerical values from general expressions in analytical form. Much of the difficulty arises from adopting a theoretical structure which recognizes the independent existence of the symmetrical components while not pressing the consequences of so doing to their logical conclusion in practice. A closer correspondence between theory and practice and a more complete assimilation of ideas is achieved by measuring the sequence components separately and directly. For verifying theoretical predictions, for providing numerical values when analysis is difficult, or design and performance information when it is impossible, this direct method is both rapid and simple.

Many textbooks make brief references of a formal nature to the measurement of sequence-component quantities, but they do little to suggest that they can provide a worth-while method of wide application in problems of real practical significance. The purpose of the present paper is to demonstrate that it is possible to measure the sequence components of voltage, current and power with the ease and reliability of ordinary routine measurements, and to provide a detailed discussion of design and circuit details for lack of which, the authors believe, the method has not hitherto attracted the serious consideration it deserves.

The circuits used are logical developments of those described in an earlier paper[1] which, however, was restricted to the measurement of sequence components of voltages only, and of their relative phase displacement. The possibility of measuring sequence components of current by similar methods was an obvious one, but power measurements were not then contemplated and are believed to be novel.

(2) METHOD FOR 3-PHASE CIRCUITS

(2.1) Voltage Bridge

A divided circuit was used in the earlier paper[1] to provide meter currents which were not only proportional to the positive- and negative-sequence components of the reference voltage, but were also in strict phase correspondence to them, as was essential for finding their relative phase displacement. There is something to be said for retaining this circuit, but it is not necessary to do so when the phase displacement between the components is not required and, largely for reasons of economy, the simpler arrangement shown in Fig. 1, which requires only

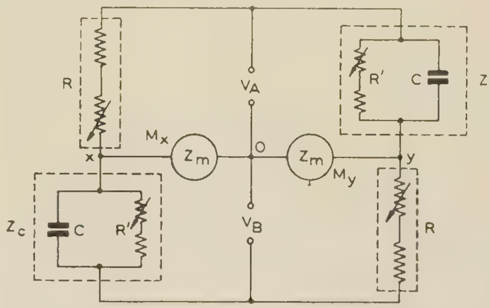

Fig. 1.—3-phase bridge circuit for the determination of sequence components of voltage.
Voltage rating 110 volts, $R = 2500$ ohms, $R' = 5000$ ohms, $C = 1\cdot0\,\mu$F.

two input transformers is preferred. The reasons for using parallel capacitive branches are explained in Section 3.3. If the bridges were to be connected directly into a system, different forms would be required, depending on the type of connection available. Instrument transformers employed in the usual way to extend the range of the bridges also allow the same bridge to be used on either star or delta circuits.

Some particular applications of this circuit to certain special cases have already been described, but the present account is a more comprehensive and critical investigation of the various circuit possibilities.

It is assumed that the zero-sequence component is absent, and the methods are thus applicable to 3-phase 3-wire systems or to 2-phase (90°) systems; there is no reason, except perhaps habit and custom, for restricting the discussion to the former, and applications of the latter are also being developed. To extend the method to 4-wire systems would not be impossible, but it is doubtful if the added complication would be worth while for the few situations where it might be useful.

Although it is not essential, it is desirable for the two halves of the bridge circuit to be identical. Referring to Fig. 1, the condition for V_{ox} and V_{oy} to be proportional to the positive- and negative-sequence components of voltage, V_{a1} and V_{a2} respectively, for a 3-phase system is $Z_c = -aR$. This relation defines a 60° capacitive impedance, and it then follows that

$$V_{a1} = I_{mx}Z_m\left[\frac{(1-a^2) + R/Z_m}{\sqrt{3}}\right]\frac{1-a^2}{\sqrt{3}} \quad . \quad . \quad (1)$$

$$aV_{a2} = V_{b2} = I_{my}Z_m\left[\frac{(1-a^2) + R/Z_m}{\sqrt{3}}\right]\frac{1-a^2}{\sqrt{3}} \quad . \quad (2)$$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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where a is the 120° operator, I_{mx} and I_{my} are the currents in the meters M_x and M_y respectively, and Z_m is the meter impedance, which is taken to be the same for both instruments but need not be so.

The terms $I_{mx}Z_m$ and $I_{my}Z_m$ are simply the voltages V_{mx} and V_{my} across the meters M_x and M_y, respectively. Thus a knowledge of either the voltages V_{mx} and V_{my} or the currents I_{mx} and I_{my} can be used to determine the sequence components V_{a1} and V_{a2} respectively, provided that the constant of proportionality is known or is absorbed as an overall scale factor. The distinction between an ammeter and a voltmeter is essentially one of relative impedance, and what is important here is the magnitude of the meter impedance, Z_m, compared with the bridge impedances. Thus, any voltmeter whose impedance is sufficiently high for the term R/Z_m to be negligible can be inserted in the bridge and will read the sequence voltage directly without further calibration of the meter—for the scale factor $[(1 - a^2)/\sqrt{3}]^2$ has unit magnitude—or re-adjustment of the bridge. Alternatively, when any ammeter with a sufficiently low impedance is used, the readings must be multiplied by $R/\sqrt{3}$, where R is the resistance used in the bridge, to give the sequence-component voltage.

When the relative impedance is all that matters, the limiting conditions just described are easily achieved, but they may not always be possible when other considerations, e.g. power consumption, are taken into account. In general, when the scale factor is complex, the instruments must be calibrated, but it will be the same for both meters if they are identical. Any phase displacements which there might be do not introduce any errors in the measurement of the sequence components.

When the capacitive impedance Z_c in Fig. 1 is replaced by an inductive impedance Z_L, the condition corresponding to the one quoted above is $Z_L = -a^2R$. Using identical 60° inductive impedances in place of Z_c in the arms of the bridge, the sequence-component voltages can be expressed as

$$aV_{a2} = V_{b2} = I_{mx}Z_m\left[\frac{(1 - a^2) - a^2R/Z_m}{\sqrt{3}}\right]\frac{1 - a^2}{\sqrt{3}} \quad . \quad (3)$$

$$V_{a1} = I_{my}Z_m\left[\frac{(1 - a^2) - a^2R/Z_m}{\sqrt{3}}\right]\frac{1 - a^2}{\sqrt{3}} \quad . \quad . \quad (4)$$

The meters which originally responded to the positive- and negative-sequence components now respond to the negative- and positive-sequence components respectively.

The choice between capacitive and inductive circuits is determined by practice rather than by theoretical considerations. Capacitors are usually preferred for a high-impedance bridge and inductors for a low-impedance bridge. A voltage bridge will usually be a high-impedance device, if only to keep the dissipated power as low as possible, and for similar reasons a current bridge will normally have a high admittance.

For a given resistance, the relation $Z_c = -aR$, for example, defines a capacitive impedance, but it does not specify it uniquely in terms of circuit components. It may be composed of a capacitor in series with a resistor, or a capacitor in parallel with a resistor. In both cases the impedance will vary with frequency, and the values are chosen to satisfy the required condition at some particular frequency, called the calibrating frequency (usually 50 c/s), at which the bridge is to be used. At this frequency there is nothing to choose between the series and parallel impedances. Where they differ is in the manner in which they respond to supply frequencies which are different from the one employed for the initial bridge adjustment, and as explained in Section 3.3, the parallel impedance form is preferred.

(2.2) Current Bridge

The circuit for the current bridge, corresponding to the voltage bridge in Fig. 1, is shown in Fig. 2. The condition for I_{mx} and I_{my} to be proportional to the positive- and negative-

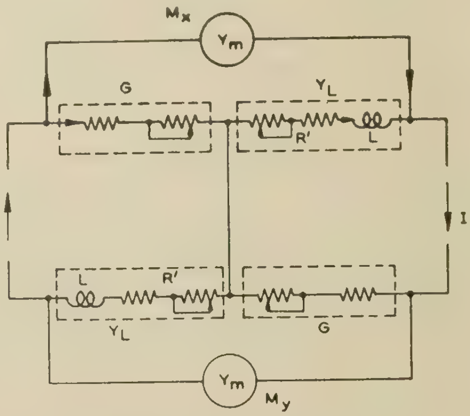

Fig. 2.—3-phase bridge circuit for the determination of sequence components of current.

Current rating 2·5 amp, R (=1/G) = 1·18 ohms, R' = 0·59 ohms, L = 3·25 mH.

sequence components of current I_{a1} and I_{a2} respectively, is $Y_L = -aG$ and it then follows that

$$I_{a1} = V_{mx}Y_m\left[\frac{(1 - a^2) + G/Y_m}{\sqrt{3}}\right]\frac{1 - a^2}{\sqrt{3}} \quad . \quad . \quad (5)$$

$$aI_{a2} = V_{my}Y_m\left[\frac{(1 - a^2) + G/Y_m}{\sqrt{3}}\right]\frac{1 - a^2}{\sqrt{3}} \quad . \quad . \quad (6)$$

where V_{mx} and V_{my} are the voltages across the meters M_x and M_y respectively, and Y_m is the meter admittance. The relation $Y_L = -aG$, rearranged, defines a 60° inductive impedance.

The terms $V_{mx}Y_m$ and $V_{my}Y_m$ are simply the currents through the meters M_x and M_y respectively.

A knowledge of either the currents I_{mx} and I_{my} or the voltages V_{mx} and V_{my} can thus be used to determine the sequence components I_{a1} and I_{a2} respectively. Using an ammeter with a sufficiently high admittance for the term G/Y_m to be negligible, the sequence components can be read directly. When a voltmeter with a sufficiently low admittance is used, the scale readings must be multiplied by $G/\sqrt{3}$, where G is the conductance used in the bridge. As in Section 2.1, when neither of these limiting conditions is even approximately true, the scale factor is complex and must be found by direct calibration.

Similar results could be deduced for a bridge employing capacitive admittances, but as a high admittance is usually required for a current bridge, inductive admittances will be used in practice in most cases.

The account of the current and voltage bridges has been presented in a manner which directs attention to the marked similarity which exists between them. This is further emphasized by comparing the analysis for the current bridge (Fig. 2 and Section 2.2) with that established earlier[1] for the voltage bridge, when it is observed that corresponding equations are reciprocals of one another. The correspondence between the circuits shown in Figs. 1 and 2 is even more detailed and simply reflects the fact that these two circuits are topological duals.

The 60° inductive impedance which is required may be composed either of a series or a parallel circuit. Only at frequencies which are different from the calibrating frequency is there a significant difference between them. The current bridge with a

series inductive impedance is the direct dual of the voltage bridge with a parallel capacitive impedance and is the one preferred in practice (see Section 3.3).

(2.3) Power Measurement

In any 3-phase 3-wire system the total power can be measured directly by the two-wattmeter method, but it is frequently desirable to know how this power is distributed between the two sequence components. In principle, all that is wanted to measure the positive-sequence component power, for example, is to connect the voltage-coil circuit of the wattmeter in place of the meter M_x in the voltage bridge, and the current coil in place of the meter M_x in the current bridge.

Assuming that R/Z_m and G/Y_m can be neglected [see eqns. (1) and (5)] the wattmeter will read the positive-sequence power directly, and a second wattmeter, connected in a similar manner, will read the negative-sequence power. If, on the other hand, a low-impedance coil is used in the voltage bridge and a high-impedance coil in the corresponding branch in the current bridge, the wattmeter will again respond to the sequence power but, though there should still be no phase error, the wattmeter reading must be multiplied by the scale factor $\frac{1}{3}RG$. The current output of the voltage bridge will not, however, exceed $\sqrt{3}(V_a/R)$ and the maximum output from the current bridge is $\sqrt{3}(I_a/G)$.

In general, the relation between the sequence power and the corresponding wattmeter reading is complex, and there are both phase and magnitude errors. The former arise from the difference in argument between the terms $Z_m(1 - a^2) + R$ and $Y_m(1 - a^2) + G$, and a correction is most simply applied by introducing a constant compensating phase-shift in either, or both, of the wattmeter coil circuits. There are a number of ways in which this can be done. For example, each meter coil could be phase-corrected to give an output response which is in exact phase correspondence with the quantity being measured. A correction for magnitude error is then achieved by applying a numerical scale multiplier, or the wattmeter can be recalibrated.

(3) DESIGN, ASSEMBLY AND TESTS

(3.1) Bridge Characteristics

(3.1.1) Impedance.

A knowledge of the effective bridge impedance is required if instrument transformers are to be used. It is easy to show that the magnitudes of the impedance presented by the voltage bridge to either of its supplies take extreme values $R/\sqrt{3}$ and $\sqrt{3}R/2$ for zero and infinite values of meter impedances respectively. For the current bridge, the corresponding limiting values of the input admittance are $G/\sqrt{3}$ and $\sqrt{3}G/2$ for zero and infinite values of meter admittances respectively.

(3.1.2) Power Dissipated.

The power dissipated in the circuit depends not only on the magnitude of the sequence components but also on their relative phase displacement. The maximum value occurs when the two sequence components are equal and V_{a2} leads V_{a1} by an angle $\pi/3$. In these circumstances the corresponding unbalanced voltages V_A and V_B are co-phasal and equal in magnitude, so that although the 3-phase condition is a rather special one, it can be simulated by a very simple single-phase test. With equal co-phasal applied voltages V, the power dissipated in the voltage bridge varies between $3V^2/R$ and $4V^2/R$ for meter impedances between zero and infinity respectively. The corresponding results for the current bridge are $3I^2/G$ and $4I^2/G$ for zero and infinite values of meter admittances respectively.

(3.2) Bridge Adjustment and Performance Tests

The most convenient procedure is, perhaps, to calculate the approximate value of the bridge components for a required value of power dissipation and then to find the precise setting by experiment, using a balanced 3-phase supply. This has the merit that stray resistance and capacitance are included in the adjustment; cumulative errors, which would otherwise arise from separate measurements, are avoided, and the setting is quickly and easily accomplished.

Thus, if the power dissipated in the parallel-impedance voltage bridge is not to exceed 20 watts for maximum input voltages $V_A = V_B = 110$ volts, the calculated values, in round figures, taking Z_m to be zero, are 2 750 ohms for the resistive branches and 1 μF and 5 500 ohms for the parallel capacitive branches. When the meter impedances are significantly different from zero, the power dissipated will be less. It could, of course, be reduced by choosing higher-impedance components, but then direct-reading voltmeters of correspondingly higher sensitivity would be required. In this particular case, using voltmeters with a sensitivity of 1 000 ohms/volt, the ratio R/Z_m is approximately 0·025 and is small enough to be neglected for many purposes. The circuit shown in Fig. 1 was therefore assembled, using wire-wound resistors and two accurately matched capacitors, and was supplied from a star-connected voltage system which had been carefully balanced. The frequency during this test was 50 c/s with a maximum permissible departure of $\pm 1/30$ c/s.

The two trimming resistors in the negative-sequence part of the circuit were then adjusted to give a zero or minimum reading on the negative-sequence meter. A residual reading at this stage usually indicates the presence of harmonics in the supply, and a more exact method in such cases is to display the bridge output voltage on a cathode-ray oscillograph and to adjust for zero 50 c/s component. The positive-sequence part of the circuit was adjusted in a similar way after reversing the phase rotation of the supply. Once the bridge was adjusted, the same balanced supply was used for calibrating the meters. In this way, with a balanced input of 100 volts, the meter reading, which should ideally be zero, was reduced to less than 0·05 volt, and the scale factor for the voltmeters, which, should be direct reading, was found to be 0·98. When ammeters are used in place of voltmeters in the voltage bridge, the current readings should ideally be multiplied by the factor $R/\sqrt{3}$ to convert them to sequence voltages [see eqns. (1) and (2)]. The measured value of R after adjustment was found to be 2 500, and the theoretical scale factor was therefore 1·45. The test figures gave a value of 1·49.

When the input voltages are co-phasal and both equal to 110 volts, and Z_m is large, the power dissipated in the circuit is a maximum. The calculated value $4V^2/R$ was 19·4 watts and the measured value was 19·5 watts. For zero values of Z_m, the calculated and observed values were both 14·5 watts. For a circuit to be used with low-impedance meters only, the power dissipated could be reduced substantially below 14·5 watts by employing a high-impedance bridge.

The theoretical value of the impedance presented by the bridge to the supply lies between the extremes 2 170 ohms for an infinite value of Z_m and 1 447 ohms for a zero value for Z_m. Corresponding measured values were 2 238 and 1 510 ohms respectively. These are well within the rating of a 110-volt 40 VA instrument transformer.

Substantially the same methods can be employed for the current bridge except that a compromise design, by which is meant one which can be used directly with either ammeters or voltmeters, cannot be achieved so satisfactorily. This is largely due to the restrictions imposed by the current transformers. The bridge was designed to present a maximum input impedance of 2 ohms, corresponding to $R = 1·15$ ohms. The measured

values after adjustment were 1·18 ohms for the resistive branches, and 0·59 ohm and 3·25 mH for the inductive branches. The maximum and minimum burdens imposed on the current transformers were 1·37 ohms for infinite Y_m and 2·07 ohms for zero Y_m, and the corresponding calculated impedances were 1·37 and 2·0 ohms respectively.

It is essential to ensure that the resistance of the inductive windings is less than $R/2$ in order to arrive at a 60° impedance by adding a series trimmer. The two inductance coils were identical in construction and were mounted at right angles. Special provision was made for tilting one of the coils, and it was fixed in that position in which separate tests showed the magnetic coupling between the two coils to be zero.

With a balanced current of 5 amp applied, the residual current on the meter which should read zero was barely detectable and the 50 c/s voltage across it, measured on a wave analyzer, was less than 10 μV.

Using good-quality voltmeters in the bridge, the scale reading should be multiplied by $G/\sqrt{3} = 0{\cdot}49$, and the factor found on test was 0·50. When ammeters were used in the bridge, the observed scale factor was appreciably different from unity, showing that the term G/Y_m [eqns. (5) and (6)] was not negligible. This simply reflects the fact that the admittances of ordinary a.c. ammeters are not sufficiently high compared with the admittances in the bridge circuit. As a further consequence of this, the maximum power dissipation in the circuit, $4I^2/G$, will not be achieved in practice, though its value can be verified for test purposes by short-circuiting the meter terminals, and the actual loss will be more nearly $3I^2/G$. As the circuit was designed for a maximum current of 2·5 amp, the last expression gives a value of 22 watts. Since, however, a bridge for use with direct-reading ammeters cannot easily be realized in practice, there is less reason for keeping G small and much to be said for designing a high-admittance circuit to suit the burden of the current transformer. In this way, the figure of 22 watts could be reduced by 50%. The bridge has frequently been used with ordinary 5 amp 7·5 VA Class-A current transformers and, although the burden exceeds the rated value, at the reduced current of 2·5 amp the estimated errors are less than 1% in magnitude and 0·5° in phase.

The measurement of sequence power is a little less straightforward in practice than the determination of sequence components of current and voltage, because of conditions imposed by the measuring instrument. A wattmeter cannot be used directly in the deceptively simple manner suggested in Section 2.3, for the impedances of the voltage- and current-coil circuits are not usually of the order which allows R/Z_m and G/Y_m, respectively, to be neglected. When, on the other hand, a low-impedance load is used in the voltage bridge and a low-admittance load in the current bridge, the current output in the first case, and the voltage output in the second, is limited and a low-range wattmeter is required.

The instrument which was used was a dynamometer voltmeter which had been modified by separating the two coils and removing the original series resistors. The full-load current was 81 mA and the impedances of the fixed and moving coils were 12·7 and 42·01 ohms. The latter was almost wholly resistive and the former had a phase angle of 39°.

With the fixed coil in, say, the positive-sequence position in the voltage bridge, the ratio Z_m/R was negligible and therefore

$$V_{a1} = \left(\frac{R}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\right)I_{mx} \quad . \quad . \quad . \quad . \quad (7)$$

from which relation the maximum current through the coil is seen to be 76 mA.

The maximum voltage available from the current bridge was 5·8 volts and the moving coil therefore required an additional series resistor of about 30 ohms. Thus, eqn. (5) can be written

$$I_{a1} = \left(\frac{G}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\right)V_{mx} \quad . \quad . \quad . \quad . \quad (8)$$

with a magnitude error of 1·6% and an error in phase of 46′. It was not thought necessary to correct for the phase error, though this could easily have been done, and the magnitude error was absorbed in the scale factor. The relation between deflection and sequence power was a linear one, and the scale was calibrated by employing balanced voltage and current systems as already described.

The arrangement proved to be quite satisfactory except when it was used in very reactive circuits for which a low-power-factor wattmeter is desirable. It is perhaps sufficient to say that a meter of this type can be employed, provided that suitable inductances or capacitances are placed in series or parallel with the instrument coils as required. It is important to observe that the corrections are made with respect to the instrument and that the bridge and its settings are in no way disturbed.

(3.3) Frequency Response

The bridge circuits are essentially pre-adjusted frequency-sensitive devices, and though it was encouraging to find that such variations of the mains frequency as there might have been during the tests produced no serious error, the account would be incomplete without some reference to the frequency effects in more general circumstances.

If α is the frequency expressed as a fraction of the calibrating frequency, the relation $Z_c = -aR$ or, what is the same thing, $R = -a^2Z_c = (\frac{1}{2} + j\sqrt{3}/2)Z_c$ must be replaced by $R = [\frac{1}{2} + j(\sqrt{3}/2)\alpha]Z_c$ for the parallel-impedance bridge shown in Fig. 1.

Applying Kirchhoff's laws to the circuit, as before, eqns. (1) and (2), after some-rearranging, can be replaced by

$$a^2(\alpha+1)V_{a1} + a(\alpha-1)V_{a2} = \frac{-2j}{\sqrt{3}}I_{mx}\left[R + Z_m\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\alpha\right)\right] \quad . \quad . \quad (9)$$

and

$$(\alpha-1)V_{a1} + (\alpha+1)V_{a2} = \frac{-2j}{\sqrt{3}}I_{my}\left[R + Z_m\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\alpha\right)\right] \quad . \quad . \quad (10)$$

Thus, when a system is unbalanced and the frequency is incorrect, eqns. (9) and (10) are simultaneous equations for the sequence-component voltages. They are not simple, but they do enable upper limits to be assigned fairly easily to the frequency error, and this is often all the information which is required.

Consider now the simpler situation when the supply is balanced but the frequency is different from the calibrating frequency. Putting $V_{a2} = 0$ in eqns. (9) and (10),

$$a^2(\alpha+1)V_{a1} = \frac{-2j}{\sqrt{3}}I_{mx}\left[R + Z_m\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\alpha\right)\right] \quad . \quad . \quad (11)$$

$$(\alpha-1)V_{a1} = \frac{-2j}{\sqrt{3}}I_{my}\left[R + Z_m\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\alpha\right)\right] \quad . \quad . \quad (12)$$

As before, there are two particular cases, corresponding to high and low meter impedances. Removing R, in the first instances from eqns. (11) and (12) and simplifying,

$$\left|\frac{V_{mx}}{V_{a1}}\right| = \frac{1+\alpha}{\sqrt{(3+\alpha^2)}},\quad \left|\frac{V_{my}}{V_{a1}}\right| = \frac{1-\alpha}{\sqrt{(3+\alpha^2)}} \quad . \quad . \quad (13)$$

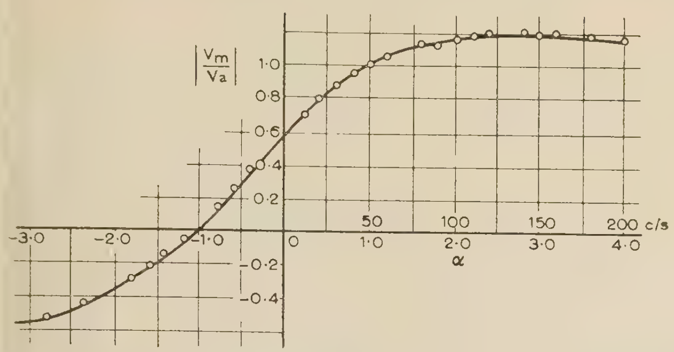

Fig. 3.—Variation of output voltage with a balanced variable-frequency input voltage when high-impedance meters are used in the parallel-impedance voltage bridge shown in Fig. 1.

The curve is the theoretical relation

$$y = \left|\frac{V_m}{V_a}\right| = \frac{1 + \alpha}{\sqrt{(3 + \alpha^2)}}$$

Negative values of α correspond to a reversal of phase sequence of the supply.

These expressions are easily verified in practice by providing a balanced variable-frequency supply of constant voltage. As shown in Fig. 3, the agreement between theory and practice is most satisfactory. The effect of a balanced negative-sequence supply of variable frequency is similarly obtained by putting $V_{a1} = 0$ in eqns. (9) and (10). It will be observed, however, that a change in sign of α is equivalent to a reversal of phase sequence of the supply, and thus a single curve represents the complete frequency performance. The first quadrant refers to the variation of a meter reading with respect to the sequence component to which it is designed to respond. The third quadrant refers, in effect, to the variation of a meter reading with respect to a reversed sequence component to which, at calibrating frequency, there would be no response at all. A similar interpretation attaches to Figs. 4 and 5.

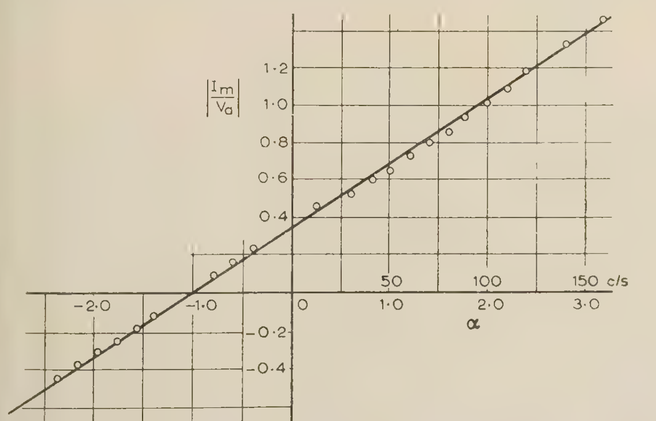

Fig. 4.—Variation of output current with a balanced variable-frequency input voltage when low-impedance meters are used in the parallel-impedance voltage bridge shown in Fig. 1.

The straight line is the theoretical relation

$$y = \left|\frac{V_m}{I_a}\right| = \frac{\sqrt{3}(1 + \alpha)}{2R}$$

i.e. for $R = 2\,500$ ohms, $y = 8 \cdot 3(1 + \alpha)$.

Negative values of α correspond to a reversal of the phase sequence of the supply.

It follows that in the general case when both sequence components are present, the response on, say, the positive-sequence voltmeter will have a value within the range

$$\frac{1 + \alpha}{\sqrt{(3 + \alpha^2)}}|V_{a1}| \pm \frac{1 - \alpha}{\sqrt{(3 + \alpha^2)}}|V_{a2}|$$

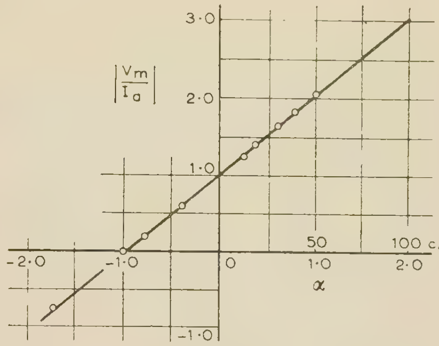

Fig. 5.—Variation of voltage output with a balanced variable-frequency input current when high-impedance meters are used in the series-impedance current bridge shown in Fig. 2.

The straight line is the theoretical relation

$$y = \left|\frac{V_m}{I_a}\right| = \frac{\sqrt{3}(1 + \alpha)}{2G}$$

i.e. for $1/G = R = 1 \cdot 18$ ohms, $y = 1 \cdot 02(1 + \alpha)$.

Negative values of α correspond to a reversal of the phase sequence of the supply.

and, furthermore, this range will be a maximum when the two sequence components are equal in magnitude. Thus, the expressions

$$\frac{2|V_{a1}|}{\sqrt{(3 + \alpha^2)}} \text{ and } \frac{2\alpha|V_{a1}|}{\sqrt{(3 + \alpha^2)}} \quad . \quad . \quad . \quad (14)$$

define upper and lower limits of the voltmeter readings. The frequency error as a fraction of the correct reading at the calibrating frequency will therefore not exceed the larger of the expressions

$$1 - \frac{2}{\sqrt{(3 + \alpha^2)}},\ 1 - \frac{2\alpha}{\sqrt{(3 + \alpha^2)}} \quad . \quad . \quad . \quad (15)$$

In the most adverse circumstances, when both sequence components are equal in magnitude and the phase displacement between them has the precise value corresponding to the second of these expressions, and the applied frequency is high, a frequency departure of 4% is accompanied by a 3% error in the meter reading. With a phase displacement corresponding to the first expression, but conditions otherwise unchanged, the error in the meter reading is reduced to less than 1%, and there will be a proportional reduction in error in all cases for smaller values of negative-sequence component.

The theoretical results corresponding to the insertion of low-impedance meters in the bridge circuits are obtained by removing Z_m from eqns. (11) and (12) and simplifying, giving

$$\left|\frac{I_{mx}}{V_{a1}}\right| = \frac{(1 + \alpha)\sqrt{3}}{2R} \text{ and } \left|\frac{I_{my}}{V_{a1}}\right| = \frac{(1 - \alpha)\sqrt{3}}{2R} \quad . \quad . \quad (16)$$

As Fig. 4 shows, there is again a close correspondence between theoretical and practical results. Repeating the arguments used in the last paragraph, the percentage error in the reading of the positive-sequence component ammeter will never be greater than the percentage frequency error, and will usually be much less.

Other things being equal, a linear frequency characteristic is generally to be preferred to one which is non-linear, but there is more to it than this. Except at high frequencies, when the product $Z_m(3/2 + j\alpha\sqrt{3}/2)$ in eqns. (11) and (12) ceases to be negligibly small, a change in frequency is not accompanied by a change in phase and, as a consequence, there is no additional phase error when using circuits of this kind for the measurement of sequence-component power.

The same general conclusions are true of the dual arrangement

which is the series-inductance current bridge using low-admittance meters, i.e. voltmeters. Theoretical and practical results are shown in Fig. 5.

The results set out in expressions (15) are intrinsic properties of the circuits and cannot therefore be modified by choice of circuit constants. It follows from the dual of eqn. (16) that there is no phase error when the current bridge shown in Fig. 2 is used with voltmeters, and the error in the reading on the positive-sequence component voltmeter in the current bridge therefore does not exceed the percentage difference between the actual frequency and the frequency used for calibrating. The magnitude error in the wattmeter reading when the current and voltage bridges are used in this way to measure power is less than $(1-\alpha)^2$. A change in frequency of 4% is accompanied by an error in measured power of less than 0·2%.

In laboratory tests the frequency is separately controlled, and frequency errors are avoidable. This is not possible at mains frequency, but the frequency variation is normally small, though it is an obvious precaution to verify this during any particular test to avoid unexpected errors. It would nonetheless be an improvement if the circuits were to be less sensitive to frequency variations. A method of frequency compensation which has been proposed[2] was wholly satisfactory for the particular purpose for which it was developed, but it would be very complicated if applied more generally. Another suggestion, which has not been fully developed, is to modify the impedance of the branches containing the measuring instruments so that, in effect, Z_m also varies with frequency.

A further possibility would be to construct an adjustable-frequency bridge (as has been done successfully for a special application at audio frequencies) employing ganged variable capacitors with settings marked directly in terms of frequency. The bridge would then be preset to the measured frequency in any particular test. As shown in Section 3.1, the bridge characteristics can be expressed in terms of the ohmic resistance branch and, as this remains unaltered, there will be no undesirable changes in the power dissipated or the input impedance with frequency adjustment.

(3.4) General

Many circuit arrangements suggest themselves: some can be rejected on inspection, and experience has shown that, of the rest, the most suitable are the parallel-capacitive voltage bridge and the series-inductive current bridge. These two circuits are duals of one another and, therefore, properly interpreted, there is a one-to-one correspondence between them, and the properties of either can be inferred from the performance of the other. Low-impedance meters are preferred in the voltage bridge and high-impedance meters in the current bridge. In this way, the power dissipated in the bridge circuits is a minimum for given circuit components, and the frequency characteristic is linear.

There is no difficulty in designing circuits for the measurement of sequence components of either voltage or current to be used with instrument transformers and ammeters or voltmeters of suitable range. As the factors to be applied to convert scale readings to sequence-component values are constants which are determined by the circuit impedances, specially calibrated meters are not required; the bridges are therefore versatile in use, and the authors believe that they could well be produced as a standard commercial article for use in industrial and teaching laboratories. For power measurements, however, the characteristics of the wattmeter are more critical, and there is less tolerance in design. For optimum performance, therefore, the circuits should be chosen to suit a particular instrument. Their use for measuring sequence components of current and voltage is in no way impaired by so doing.

(4) 2-PHASE (90°) SYSTEMS

Just as symmetrical-component principles are not restricted to 3-phase systems, so the methods described for measuring the sequence components can be generalized. In particular, they can be applied to the so-called industrial 2-phase systems, which are in reality 4-phase systems with no zero-sequence component. All the significant results for the 2-phase bridge circuits can be deduced, almost by formal transposition, from corresponding statements referring to the 3-phase circuits.

The condition for V_{ox} and V_{oy} in Fig. 1 to be proportional to the positive- and negative-sequence components respectively, when the unbalanced applied voltages are given by $V_A = V_{a1} + V_{a2}$ and $V_B = -jV_{a1} + jV_{a2}$, is $Z_c = -jR$. Thus Z_c in this case is a pure capacitance satisfying the numerical relation $|Z_c| = R$ at the calibrating frequency. In general, this relation can be written $R = j\alpha Z_c$ where, as before, α is the applied frequency expressed as a fraction of the calibrating frequency. Making these substitutions in Fig. 1 and applying Kirchhoff's laws,

$$(\alpha+1)V_{a1} + (1-\alpha)V_{a2} = I_{mx}[R + Z_m(1+j\alpha)] \quad . \quad (17)$$

$$(\alpha-1)V_{a1} + (\alpha+1)V_{a2} = (-j)I_{my}[R + Z_m(1+j\alpha)] \quad . \quad (18)$$

$$V_{a1} = I_{mx}\left[\frac{R + Z_m(1+j)}{2}\right] \quad . \quad . \quad . \quad . \quad (19)$$

$$V_{a2} = (-j)I_{my}\left[\frac{R + Z_m(1+j)}{2}\right] \quad . \quad . \quad . \quad (20)$$

from which equations the results for either low- or high-impedance meters are readily deduced by removing Z_m or R, respectively.

The effect of applying a balanced 2-phase supply at a frequency different from α is found by removing V_{a2} from eqns. (17) and (18), giving

$$(\alpha+1)V_{a1} = I_{mx}[R + Z_m(1+j\alpha)] \quad . \quad . \quad (21)$$

$$(\alpha-1)V_{a1} = (-j)I_{my}[R + Z_m(1+j\alpha)] \quad . \quad . \quad (22)$$

As in Section 3.3, for the 3-phase circuit, the frequency response is linear when low-impedance meters are used, i.e. when Z_m can be neglected. The impedance presented by the bridge at its input terminals has a magnitude of $R/\sqrt{2}$ and the maximum power dissipated, when V_A and V_B are equal and co-phasal, is $2V^2/R$ (see Sections 3.1.1 and 3.1.2).

Similar results can, of course, be quoted for the 2-phase analogue of the current bridge shown in Fig. 2, but the difficulty here is the practical one of realizing an inductance with a phase angle which is not appreciably different from 90°.*

In the first instance, therefore, the voltage bridge shown in Fig. 6 was used for both purposes. Sequence-component currents were evaluated in terms of the voltages established across resistors R_S when the unbalanced currents were passed through them. The choice of R_S is determined by the permissible burden of the associated transformers on the one hand and the sensitivity of the bridge instruments on the other. With a maximum current of 2·5 amp and $R_S = 1{\cdot}2$ ohms, the bridge input is 3·0 volts, and when milliammeters with a range 0–1·0 mA are used, eqn. (19) gives $R = 6000$ ohms. Fig. 6 shows the measured values after assembly and adjustment, which was very similar to the method described in Section 3.2.

For direct-voltage measurements, series limiting resistors R_L are used in the ordinary way and, as there are not the same

* The essential condition to be satisfied is that the branch impedances should be equal in magnitude and in quadrature in phase, and the relation $Z_c = -jR$ is a special case. It should therefore be possible to compensate for the unavoidable resistance associated with the inductance by adding capacitance to the resistive branch, and this possibility is being investigated.

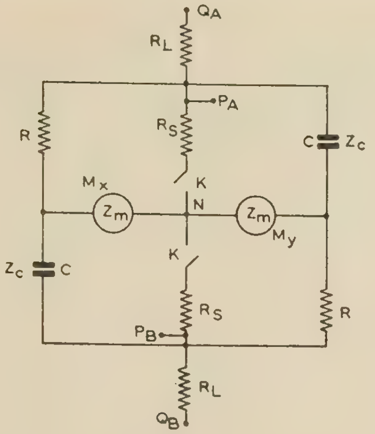

Fig. 6.—Low-voltage 2-phase (90°) bridge circuit, with shunts and multipliers, for determining the sequence components of either voltage or current.

Rating 110 volts, 2·5 amp, $C = 0 \cdot 6\,\mu F$, $R = 5\,220$ ohms, $R_S = 1 \cdot 19$ ohms, $R_L = 50\,000$ ohms.
Current measurements: close switches K, connect current transformer secondaries between P_A and N, P_B and N.
Voltage measurements: open switches K, connect potential transformer secondaries between Q_A and N, Q_B and N.

reasons for restricting the bridge input to 3·0 volts, higher-range meters can be used. Using the bridge circuit alone, without either shunts or multipliers, the relation between the low-voltage balanced 2-phase input and the milliameter reading was found to be quite linear. The observed scale-factor was 2·66 volts/mA and the theoretical value was $R/2 = 2 \cdot 61$ [see eqn. (19)]. For higher voltages, with R_L inserted, the relation was equally linear, and the observed scale factor was 37·7 volts/mA. When used as a current bridge, with shunts R_S inserted, there was again a linear relation between input current and the milliammeter reading. The power dissipated is determined primarily by the values of the shunts and multipliers, for that associated with the bridge circuit alone is of the order of milliwatts.

(5) APPLICATIONS

(5.1) Elementary Tests

A cardinal principle in symmetrical-component theory asserts that there is no interaction between the different-sequence systems, and, in particular, it is assumed in machine applications that impedance or admittance parameters which are determined under balanced polyphase conditions preserve their identity unchanged when the conditions are unbalanced. The evidence in support of this assumption is indirect and relies on an observed overall agreement between theory and practice. By using the bridges these assumptions can be put to direct experimental test.

Using a circuit arrangement previously employed for an electrical differential[3] which enables the sequence components to be controlled and measured independently, a variable unbalanced 3-phase voltage system was synthesized and connected to a balanced static impedance load. The relation between either of the sequence components of voltage and the corresponding sequence component of current was exactly linear and independent of the phase and magnitude of the other. Similarly, the relation between either of the sequence components of power and the product of corresponding sequences of current and voltage was also linear and independent of the other, thus verifying that only components of the same sequence react to give power. The slopes of these lines gave a value of impedance in one case, and phase angle in the other, in close agreement with the known values for the load impedance employed.

The test is of greater practical significance when the balanced passive network is replaced by the windings of a 3-phase 400-volt 5 h.p. squirrel-cage motor with a rated full-load current of 9·8 amp. The two sequence components should be equal at standstill, and in any event they should be constant, except for the effect of saturation of the leakage paths. These are substantially the conclusions to be drawn from the test results shown in Fig. 7.

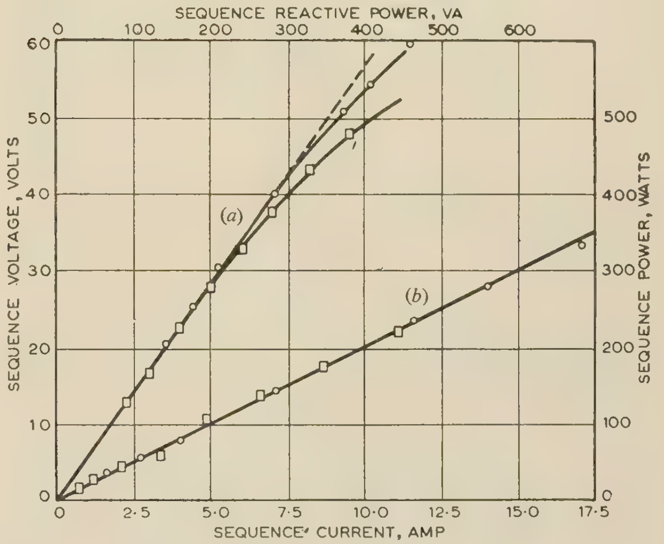

Fig. 7.—Measured values of sequence components for a 3-phase squirrel-cage induction motor at standstill.

In the absence of saturation, i.e. in the linear range, the positive- and negative-sequence impedances are equal. $|Z_1| = |Z_2| = 5 \cdot 6$ ohms, $\phi = 60°$.
—○—○—○— One phase-sequence component only.
—□—□—□— One phase-sequence component constant (10 volts, 1·8 amp) and the other component variable.
Curves (a) refer to sequence-voltage sequence-current axes.
Line (b) refers to sequence-power, sequence reactive power axes.

Except at standstill, the sequence impedances are not equal, and Figs. 8 and 9 show test results when the rotor was driven at synchronous speed. Around normal running speeds, the negative-sequence impedance is not much different from its standstill value and is affected by saturation of the leakage paths. The positive sequence, on the other hand, is more closely affected by saturation of the main magnetic circuit.

In all cases the effects of saturation are more pronounced when both sequence components are present, and in this respect, therefore, they are not independent as the simple theory presupposes. It is not easy in the ordinary event to take non-linearities into account, but the bridge circuits enable the quantities to be measured even if they cannot be calculated.

(5.2) Sequence Rejector Circuit

It is occasionally useful to regard a sequence-component network as a rejector circuit with respect to the particular component to which it does not respond. When a negative-sequence component circuit, for example, is presented with a supply which consists of a positive-sequence component at the circuit calibrating frequency, and a second balanced system of either sequence and any other frequency, the first is effectively eliminated from the output. If the circuit used is one with a linear frequency response, and the frequency of the second system is known, the magnitude of the non-standard frequency component can be found.

This is not the unlikely example it might at first appear to be, for, as is well known, the stator currents in an unsymmetrical-

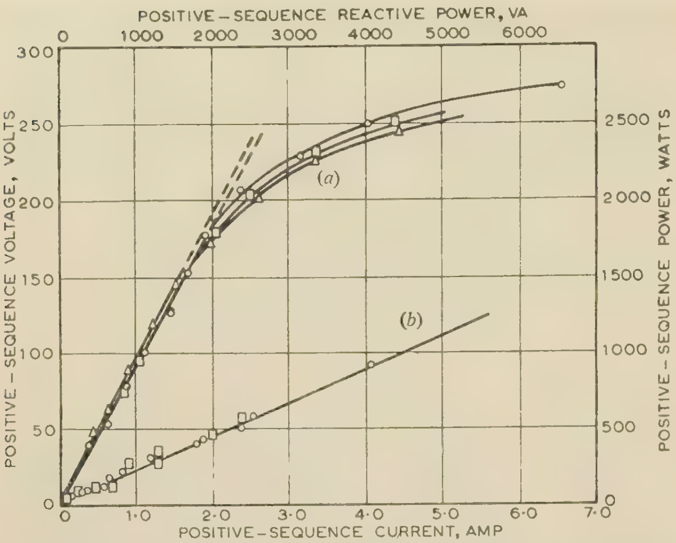

Fig. 8.—Measured values of positive-sequence component quantities for a 3-phase squirrel-cage induction motor driven at synchronous speed.

In the linear region $|Z_1| = 37\cdot5$ ohms, $\phi = 77°$.
—○—○—○— Variable positive-sequence voltage only.
—□—□—□— Variable positive-sequence voltage, fixed negative-sequence voltage (10 volts, 2·03 amp).
—△—△—△— Variable positive-sequence voltage, fixed negative-sequence voltage (20 volts, 4·07 amp).

Curves (*a*) refer to positive-sequence voltage and current axes.
Line (*b*) refers to positive-sequence power and reactive-power axes.

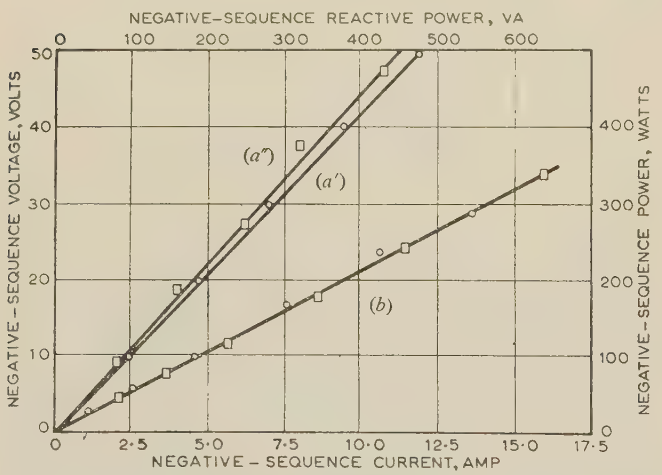

Fig. 9.—Measured values of negative-sequence component quantities for a 3-phase squirrel-cage induction motor driven at synchronous speed.

In the linear region $|Z_2| = 4\cdot2$ ohms, curve (a').
$|Z_2| = 4\cdot45$ ohms, curve (a'').
—○—○—○— Variable negative-sequence voltage only.
—□—□—□— Variable negative-sequence voltage, fixed positive-sequence voltage (150 volts, 5·0 amp).

Lines (*a*) refer to negative-sequence voltage and current axes.
Line (*b*) refers to negative-sequence power and reactive-power axes.

rotor induction motor have two components, both of which are balanced, one at supply frequency f_0 and the other at a frequency $(1\text{–}2s)f_0$. The method outlined above provides a convenient means of isolating the asynchronous term, which is of special interest in a discussion of the half-speed effects with which it is associated, and it has been used to investigate the starting and running-up problem of a half-speed synchronous motor.[4] It is hoped to give a more complete account on a future occasion.

(5.3) General

The measuring techniques described have obvious applications in transmission systems, and they have an educational value in routine laboratory teaching. They were primarily developed for investigating general problems of the asymmetrical operation of rotating polyphase machines, as was described in digest form in an earlier issue of the *Journal*.[5] Asymmetry is sometimes introduced deliberately to produce particular performance characteristics; at other times it is unavoidable, and measures must be taken to reduce its effect to a minimum. A particular application to the classic Ferraris–Arno phase-convertor is described on page 538, and it is hoped to present an account of the comparison between the 3-phase and 2-phase arrangements on a future occasion. Arising from this work, tests have been made on a proposed phase-and-frequency convertor, and preliminary results are encouraging. The possibility of using a bridge circuit as a detector in a control system for automatic balancing under variable-load conditions has been envisaged.

(6) ACKNOWLEDGMENTS

The work described has been done in the Electrical Engineering Department of the University of Bristol, and the authors are grateful for the facilities which they have enjoyed. They hope that the many Honours and Postgraduate students who have assisted in one way or another with either the construction or testing of the bridge networks, will be content with a general acknowledgment for the assistance they have given.

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(8) APPENDIX

The unbalanced currents I_A, I_B, I_C of a 3-phase system can be expressed completely and uniquely in terms of two balanced systems of opposite phase sequence, provided that $I_A + I_B + I_C = 0$.

The positive- and negative-sequence components I_{a1} and I_{a2} are then given, respectively, by

$$I_{a1} = \frac{I_A - a^2 I_B}{\sqrt{3}} \frac{1 - a^2}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad (23)$$

$$I_{a2} = \frac{I_A - a I_B}{\sqrt{3}} \frac{1 - a}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad (24)$$

Now, referring to the circuit shown in Fig. 2 and applying Kirchhoff's laws,

$$I_A = GV_G + Y_m V_{mx} \quad . \quad . \quad . \quad . \quad (25)$$

$$I_B = Y_L V_L + Y_m V_{mx} \quad . \quad . \quad . \quad . \quad (26)$$

and

$$V_G + V_L = V_{mx} \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

When G and Y_L are equal in magnitude but differ in phase by 60°, i.e. when $G = -a^2 Y_L$, Y_L can be eliminated from eqns. (25) and (26). By comparing the result with that of eqn. (23), the positive-sequence component can be expressed as

$$I_{a1} = V_{mx}\left[\frac{G + Y_m(1 - a^2)}{\sqrt{3}}\right]\frac{1 - a^2}{\sqrt{3}} \quad . \quad . \quad (28)$$

There is a similar result, eqn. (6), for the negative-sequence component.

The form and style of this analysis is essentially the same as that set out for the voltage bridge in the paper referred to earlier[1] and it arises because the circuits are reciprocally related and corresponding terms are therefore duals of one another. To preserve this duality in detail, when Z_c in Fig. 1 is chosen to be a resistor in parallel with a capacitor, Y_L in Fig. 2 must be taken to be a resistor in series with an inductor. The formal similarity which, as a consequence, then exists between the two circuits is thought to be a desirable feature and is well illustrated by comparing corresponding expression for power loss and input impedance quoted in Section 3.1.

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SYMMETRICAL-COMPONENT ANALYSIS APPLIED TO PHASE CONVERTORS OF THE FERRARIS–ARNO TYPE

By J. E. BROWN, B.Sc., Ph.D., and R. L. RUSSELL, M.Sc., Associate Members.

(*The paper was received* 17*th February*, 1958.)

SUMMARY

The paper provides a theoretical explanation, in symmetrical-component terms, of the N-machine capacitor-Ferraris–Arno phase-convertor in a manner which clearly shows the purpose of the so-called pilot motor and includes the single-phase motor as a special case. It is shown that a perfectly balanced 3-phase output can be obtained, but that the ideal conditions required are not likely to be encountered in practice. A theoretical expression for minimum unbalance is established and verified by practical tests using bridge networks for the direct measurement of sequence-component quantities.

LIST OF SYMBOLS

V = Single-phase line voltage.
V_A, V_B, V_C = Phase voltages of a machine.
I = Single-phase line current.
I_A, I_B, I_C = Phase currents of a machine.
Y = Admittance.
θ = Phase angle of admittance.
1, 2, 0 = Suffixes to denote positive-, negative- and zero-components, respectively, of phase A.
n = Suffix to denote the general machine, where for an N-machine system $n = 1, 2 \ldots N$.
p = Suffix to denote the pilot motor corresponding to the particular case of $n\,(= p) = 1$.

On all graphs theoretical results are shown as full-line curves and experimental results are denoted by circles.

(1) INTRODUCTION

It is common knowledge that a 3-phase induction motor will run satisfactorily on a single-phase supply, and the general performance characteristics under these conditions are quite well known. The motor is not self-starting, but, once in motion, it will readily run up to a speed which, on no load, is only a little less than that for normal 3-phase operation and the voltages at the terminals of the machine are then very nearly balanced.

One solution, in principle, to the starting problem is to provide the motor with a more or less balanced supply, at least initially, and the simplest practical method employs some form of balancer —usually a capacitor in series with the otherwise disconnected, or auxiliary, phase winding and one line of the single-phase supply. Although the capacitor is used primarily as a starting device, it is desirable to retain some capacitance under running conditions, for its effect is to produce voltages at the terminals of the motor which tend to approach perfect balance.

With few qualifications, the same arguments and methods can be applied to 2-phase machines. Indeed, single-phase motors in the low- and fractional-horse-power range usually have a 2-phase (90°) winding, and this form of operation has been well documented and design practice is firmly established. It is nevertheless common industrial practice to meet occasional demands for relatively large single-phase motors, of say 5 h.p. or more, by using a standard 3-phase machine as a so-called 'split-phase' capacitor motor. The corresponding theory is rather less satisfactory, although Habermann[1] has proposed an equivalent circuit in a form suitable for a network analyser. The method of computing the capacitance required is, however, indirect and of an iterative kind requiring repeated operations on the analyser. These and associated problems are likely to assume a greater importance with major developments in a.c. traction installations and the increased demands which there will be for auxiliary drives for railway rolling stock.

When a 3-phase machine is running steadily on no-load, the balanced, or nearly balanced, voltages set up at the machine terminals can be regarded as an established 3-phase voltage system and used as such to supply additional 3-phase induction motors in the ordinary manner. In a sense, the first motor—often referred to as a pilot motor—can be regarded as a single-phase/3-phase convertor. It is, in its essentials, the 3-phase version of the classic Ferraris–Arno method of phase conversion in which 2-phase machines were originally employed. Maggs[2, 3] has developed the use of capacitors for starting the pilot motor and has discussed their effect on the symmetry of the converted supply, under running conditions, for variations of 3-phase load. The corresponding theoretical work is related to the analogy between 2-phase and 3-phase systems. Akhunlar,[4] on the other hand, uses symmetrical-component theory but restricts his account to the simple Ferraris–Arno system without capacitors.

The explanation advanced in the present paper relies on a systematic application of symmetrical-component principles which, properly applied, have been shown in an earlier paper[5] to yield analytical solutions to the general problem of a single 3-phase induction motor operating with asymmetrically connected primary windings. The general solution of the capacitor-Ferraris–Arno system—which is not, of course, restricted to the use of one load motor—includes as particular cases a number of features of special theoretical interest or practical importance.

In comparing theory and practice considerable use will be made of the sequence-component measuring techniques which the authors have described in the preceding paper (see page 529).

(2) ANALYSIS

(2.1) General Problem

The capacitor-Ferraris–Arno convertor system in generalized form consists of a pilot motor and a number of load motors, as shown in Fig. 1. A suffix n will be used to denote the nth machine where $n = 1, 2 \ldots N$, and the first machine, for which $n = 1$, will be taken to be the pilot motor—although, as will be seen later, this distinction is somewhat arbitrary. It is convenient to use the suffix p rather than 1, which the notation strictly demands, in order to identify the pilot motor.

The first step in the analysis is to express Kirchhoff's laws in terms of the phase voltages and currents to derive the so-called 'inspection' equations. Thus, for any machine,

$$V - V_{An} + V_{Bn} = 0 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$I_{An} + I_{Bn} + I_{Cn} = 0 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Dr. Brown and Mr. Russell are in the Department of Electrical Engineering, University of Bristol.

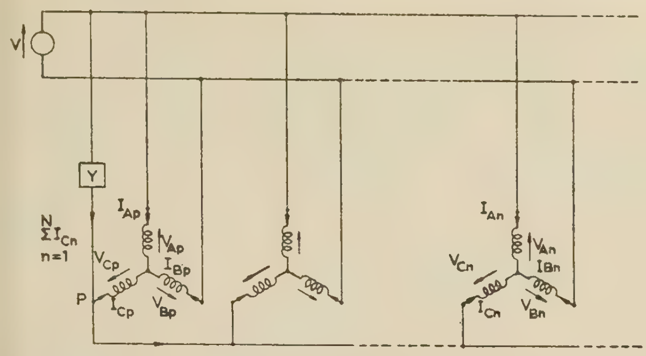

Fig. 1.—Circuit diagram for an N-machine capacitor-Ferraris–Arno phase convertor.

Y is a general admittance representing a static phase balancer which, in practice, is usually a capacitor.

and for any machine and the pilot motor,

$$V_{Bp} - V_{Cp} - V_{Bn} + V_{Cn} = 0 \quad . \quad . \quad . \quad . \quad (3)$$

At the junction P,

$$Y[V_{Cp} - V_{Ap}] + \sum_{n=1}^{N} I_{Cn} = 0 \quad . \quad . \quad . \quad . \quad (4)$$

These four equations are sufficient to determine the sequence-component voltages in the network. If V_{1n}, V_{2n} and V_{0n} denote the positive-, negative- and zero-sequence components, respectively, corresponding to phase A of the nth machine, then, as shown in Section 7.1,

$$V_{1n} = \frac{V}{\sqrt{3}}\frac{1-a}{\sqrt{3}}\frac{(1-a)Y + \sum_{1}^{N} Y_{2n}}{3Y + \sum_{1}^{N} Y_{1n} + \sum_{1}^{N} Y_{2n}} \quad . \quad . \quad (5)$$

$$V_{2n} = \frac{V}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\frac{(1-a^2)Y + \sum_{1}^{N} Y_{1n}}{3Y + \sum_{1}^{N} Y_{1n} + \sum_{1}^{N} Y_{2n}} \quad . \quad . \quad (6)$$

$$V_{0n} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where Y_{1n} and Y_{2n} are the respective positive- and negative-sequence admittances per phase, V is the single-phase supply voltage, a is the unit complex operator $\varepsilon^{j2\pi/3}$ and $n = 1, 2, - \ldots N$.

From eqn. (2), which, in effect, states that there are no zero-sequence components of current, it follows that there cannot be any zero-sequence voltages, as is summarized in eqn. (7). It follows from eqn. (5) that the positive-sequence component voltage is the same for all machines, and likewise, from eqn. (6), that they all have the same negative-sequence voltage.

From the general equations (5) and (6) particular cases can be deduced by purely formal substitutions and these, in turn, assist in an interpretation of the general problem.

(2.2) Particular Cases

(2.2.1) Single-Phase Operation of a 3-Phase Motor.

The equations for the sequence voltages when a 3-phase star-connected machine is used as a single-phase motor with the end of one phase winding unconnected and the remaining two ends connected to a single-phase supply are readily found from eqns. (5) and (6) by putting $N = 1$ and $Y = 0$. Thus, omitting the second suffix, which has no significance when considering a single motor,

$$V_1 = \frac{V}{\sqrt{3}}\frac{1-a}{\sqrt{3}}\frac{Y_2}{Y_1+Y_2} = \frac{V}{\sqrt{3}}\frac{1-a}{\sqrt{3}}\frac{1}{1+Y_1/Y_2} \quad . \quad (8)$$

$$V_2 = \frac{V}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\frac{Y_1}{Y_1+Y_2} = \frac{V}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\frac{1}{1+Y_2/Y_1} \quad . \quad (9)$$

Corresponding expressions for the sequence currents are

$$I_1 = V_1 Y_1 = \frac{V}{\sqrt{3}}\frac{1-a}{\sqrt{3}}\frac{Y_1 Y_2}{Y_1+Y_2} \quad . \quad . \quad (10)$$

$$I_2 = V_2 Y_2 = \frac{V}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\frac{Y_1 Y_2}{Y_1+Y_2} \quad . \quad . \quad (11)$$

Not only are these results consistent with those deduced from a correct interpretation of the counter-rotating field principle applied to the single-phase machine, but they also demonstrate clearly the fallacy in the arguments which seek an explanation in terms of two polyphase machines supplied at constant voltage. Thus it is correct to resolve the stationary pulsating stator field (or m.m.f.) into two components of equal magnitude and equal but opposed angular velocities, as is usually done, for eqns. (10) and (11) show that the positive- and negative-sequence components of the primary current are equal in magnitude, though not in phase, for all values of Y_1 and Y_2, i.e. at all speeds. Except at zero speed, the stator-field components have different angular velocities relative to the rotor, and thus the secondary e.m.f.'s (and hence the rotor currents) are equal only at standstill. It follows that it is generally incorrect to assume that the net resultant oppositely rotating fields have the same magnitude. This is illustrated by eqns. (8) and (9), which show that the sequence voltages are equal only when $Y_1 = Y_2$, i.e. at standstill. For all other speeds $|Y_2| > |Y_1|$, and therefore $|V_1| > |V_2|$, as shown in Fig. 2.

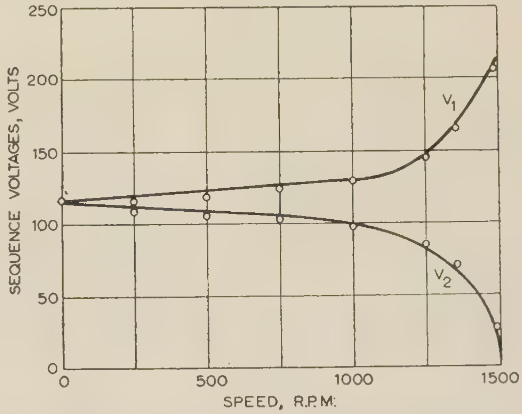

Fig. 2.—Variation of sequence voltages with speed for simple single-phase operation of a 3-phase machine.

(2.2.2) Single-Phase to 3-Phase Conversion.

The basis for the operation of a 3-phase machine as a phase-convertor resides in the fact that the positive-sequence component of voltage exceeds the negative-sequence component at all running speeds. That there are, however, inherent limitations in the simple machine used in this way is clear from eqns. (8) and (9).

The condition for the 3-phase voltage system at the terminals of the machine to be balanced is simply that there should be no negative-sequence component, i.e. from eqn. (9), $|Y_2| \gg |Y_1|$. It follows from eqn. (8) that $|V_1|$ then approaches $|V|/\sqrt{3}$, as

it should. The admittance Y_2, which is approximately the reciprocal of the leakage impedance, differs very little between standstill and full speed, whereas Y_1 decreases appreciably with increase in speed, as shown by Figs. 2 and 3 taken together. In practice, therefore, the nearest approach to ideal conditions is achieved with the motor running on light load, when $|Y_2|/|Y_1|$ may be about 15 : 1. It follows that the leakage reactance for a phase convertor of the kind considered should be reduced to a minimum, but even for a well-designed machine the output voltages will by no means be perfectly balanced.

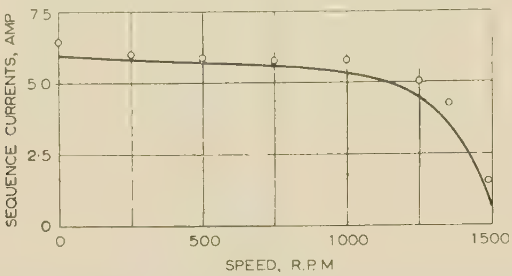

Fig. 3.—Variation of sequence currents with speed for simple single-phase operation of a 3-phase machine.
The two sequence components are equal at all speeds.

(2.2.3) The 3-Phase Motor as a Single-Phase Capacitor Motor.

When all the machines except the pilot motor in the general arrangement shown in Fig. 1 are removed, what is left is a 3-phase machine connected to a single-phase supply, and appropriate theoretical expressions can be deduced from the general analysis by taking limiting conditions to correspond. Putting $n = 1$ in eqns. (5) and (6) and dropping the suffix, since only one machine is being considered, we find

$$V_1 = \frac{V}{\sqrt{3}}\frac{1-a}{\sqrt{3}}\frac{Y(1-a)+Y_2}{3Y+Y_1+Y_2} \quad . \quad . \quad (12)$$

$$V_2 = \frac{V}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}}\frac{Y(1-a^2)+Y_1}{3Y+Y_1+Y_2} \quad . \quad . \quad (13)$$

The principal problem in operating a 3-phase machine in this way is to determine the optimum value of the admittance Y to be employed for a given machine under given conditions. It is usual, in practice, to provide one capacitance for starting and a somewhat lower value for normal running, and although Y is usually referred to in terms of capacitance, it is a general admittance in the above equations. If it is accepted that the purpose of the phase-balancer is to minimize the negative-sequence component, the ideal value of Y can be found in precise terms. Thus, from eqn. (13) the negative-sequence voltage, V_2, is zero when $Y = -\dfrac{Y_1}{\sqrt{3}}\dfrac{1-a}{\sqrt{3}}$.

For all normal speeds of the motor, Y_1 corresponds to an inductance and it can therefore be written $Y_1 = |Y_1| \angle{-\theta_1}$, where $0 < \theta_1 < 90°$. For perfect balance, therefore,

$$Y = \frac{|Y_1|}{\sqrt{3}}\angle{150° - \theta_1} \quad . \quad . \quad . \quad . \quad (14)$$

from which it follows that, for all practical purposes, the imaginary component of Y is positive.

Eqn. (14) shows that for the particular value $\theta_1 = 60°$, perfect balance can be realized by employing a pure capacitance. For values of θ_1 greater than 60° the vector Y lies in the first quadrant and its real component is therefore positive. In practice, although the value of θ_1 may well be somewhat larger than 60° at standstill, over the greater part of the speed range, and in the region of normal running speed, θ will normally be less than 60° and the required real component of Y will be negative. This condition cannot be satisfied by passive elements, and under normal working conditions, therefore, although the negative-sequence voltage can be reduced to a minimum, it cannot be eliminated completely. The value of Y corresponding to minimum conditions is also purely capacitive and can be found graphically, as shown in Section 7.2. As a first approximation, the required admittance is equal to the imaginary part of the precise value given by eqn. (14).

In a complete Ferraris–Arno system the pilot motor usually runs on no load and the value of θ_1 for this machine will exceed 60°, so that Y will have a positive real part corresponding to a resistive component. As shown in Section 2.3, however, the optimum value for Y depends on the number of machines in the system and it is not, in fact, necessary to introduce additional resistance.

The total current taken by the 3-phase motor from the single-phase supply can be synthesized from the sequence currents, as follows:

$$I(= -I_B) = -(a^2I_1 + aI_2) = -(a^2V_1Y_1 + aV_2Y_2) \quad . \quad (15)$$

Substituting for V_1 and V_2 from eqns. (12) and (13) gives

$$I = V\left(\frac{YY_1 + Y_1Y_2 + Y_2Y}{3Y + Y_1 + Y_2}\right) \quad . \quad . \quad . \quad (16)$$

For perfect balance, Y is given by eqn. (14), and therefore

$$I(= -I_B) = \frac{VY_1}{\sqrt{3}}\frac{1-a^2}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad (17)$$

It follows from the last expression that the angle by which the single-phase current lags the single-phase applied voltage is $(\theta_1 - 30°)$. As shown earlier, a zero value of V_2 is possible only for values of θ_1 exceeding 60°, and the phase angle of the machine cannot therefore be less than 30°. Thus the power-factor does not exceed 0·866 for exactly balanced operation. When, as usually happens, θ_1 is less than the critical value and the value of V_2 is a minimum but different from zero, eqn. (17) is only an approximate form of the exact equation (16), but it indicates that in these circumstances the approximate phase angle $(\theta_1 - 30°)$ may be less than 30° and the power factor rather better than 0·866.

It is clear from eqn. (14) that Y should vary continuously with speed. In practice, two values are commonly used, one during starting and another of lower value for continuous running.

Under steady running conditions without a phase-balancing admittance, $|V_2|$ is relatively low, and even allowing for large stray load losses, the corresponding reverse torque does not seriously affect the performance. The negative-sequence current is, however, equal to the positive-sequence current in magnitude and the copper losses are consequently doubled. The addition of an appropriate balancing admittance at the normal running speed results in a significant reduction in copper losses and a more modest improvement in the torque.

The insertion of a suitable value of Y to give a minimum negative-sequence component at standstill will usually give a satisfactory run-up performance, but considerations of symmetry are not the only ones to be taken into account. A fairly simple expression can be derived for a value of Y which gives maximum starting torque, but at the expense of higher starting currents. These arguments are not applicable to a phase-convertor system, for the pilot motor in such an arrangement is not called upon to supply mechanical power.

(2.3) The Complete Ferraris–Arno System

The simple Ferraris–Arno system without the auxiliary balancer is, perhaps, of theoretical interest rather than practical importance, but it provides a useful approach to the more general case and will be considered briefly in the first instance. The representative equations are obtained from eqns. (5) and (6) by putting $Y = 0$, and the results are similar to those obtained by Akhunlar:[4]

$$V_{1n} = \frac{V}{\sqrt{3}}\,\frac{1-a}{\sqrt{3}}\,\frac{\sum_1^N Y_{2n}}{\sum_1^N Y_{1n} + \sum_1^N Y_{2n}} \quad . \quad . \quad (18)$$

$$V_{2n} = \frac{V}{\sqrt{3}}\,\frac{1-a^2}{\sqrt{3}}\,\frac{\sum_1^N Y_{1n}}{\sum_1^N Y_{1n} + \sum_1^N Y_{2n}} \quad . \quad . \quad (19)$$

The condition for V_{2n} to be small is simply

$$\frac{\left|\sum_1^N Y_{2n}\right|}{\left|\sum_1^N Y_{1n}\right|} \gg 1 \cdot 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

from which it follows that this low value for a complete system of N machines cannot be smaller than the lowest value obtained for any one of them alone; and for a single machine, as shown earlier, V_2 is least on light load. The authors have adopted the notation due to Maggs in referring to a particular machine as the pilot motor. In fact, any machine for which $|Y_2/Y_1|$ is greater than the overall ratio given in eqn. (20) will assist in the phase-conversion process. It follows that the symmetry of the system as a whole is largely predetermined and cannot be modified by adjustment to meet changing conditions.

The greater the load on a particular machine, the more unsymmetrical does the system as a whole become, and some auxiliary form of phase-balancing is clearly desirable.

The arguments relating to the capacitor-Ferraris–Arno system are precisely those advanced in Section 2.2.3 and the corresponding equations are generalized by putting $\sum_1^N Y_{1n}$ for Y_1 and replacing Y_2 by $\sum_1^N Y_{2n}$. For example, the condition for perfect balance of a complete system is

$$Y = -\left[\frac{\sum_1^N Y_{1n}}{\sqrt{3}}\right]\frac{1-a}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad (21)$$

It is this result which provides the theoretical justification for the practice[3] of assigning some proportion of the total admittance required to each load machine, so that it is employed only when the particular machine is connected to the system.

It further follows, as before, that for Y to have a positive real component, the phase angle of $\sum_1^N Y_{1n}$ must not be less than 60°. The function of the pilot motor in this case is therefore much more specific than in the simple system. For perfect balance and for Y to be purely capacitive, Y_{1p} should be such that the overall phase angle of $\sum_1^N Y_{1n}$ is 60°. Unfortunately, for this to be achieved in practice, the rating of the pilot motor would need to be excessively large compared with the load motor, as reference to a typical induction-motor circle diagram will show. The practicable alternative, therefore, is to design for a minimum value of negative-sequence component, and the correct value of Y can be found from the construction set out in Section 7.2, using as the given admittances $\sum_1^N Y_{1n}$ and $\sum_1^N Y_{2n}$. For reasons already explained, the power factor may be rather better than $0 \cdot 866$.

It will be left for a future occasion to explain the manner in which 2-phase systems are superior in some respects to 3-phase systems for the applications here described.

(3) PRACTICAL RESULTS

Two identical 3-phase 4-pole star-connected 400-volt 1·0 h.p. induction motors were used for the tests, which were all carried out at the full rated voltage. For loading purposes, one motor was directly coupled to a d.c. machine of similar rating as part of a Ward Leonard set which was used to vary the speed from standstill to synchronism.

One machine was tested over the whole speed range as a simple single-phase motor, and at normal speed as a capacitor motor. The tests were then repeated with a second machine employed as a pilot motor. A comprehensive series of test results has been compiled and a few of the more significant of these, in relation to the theoretical principles adopted, have been selected.

Figs. 2 and 3 compare theoretical and practical results for the simple single-phase motor for a range of speed from standstill to synchronism. The calculated values were derived from eqns. (8) and (9) using values of Y_1 and Y_2 determined in separate tests. The practical values in these and other tests were measured directly, using the sequence-component bridges described in the preceding paper (page 529).

The two sequence components of current, Fig. 3, were found to be the same at all speeds, as theory demands, and the voltage curves, Fig. 2, clearly demonstrate the phase-conversion effect. At zero speed, $|V_2/V_1| = 1$, whereas at a full-load speed of 1 460 r.p.m. it is $0 \cdot 19$ and at synchronous speed is less than $0 \cdot 10$.

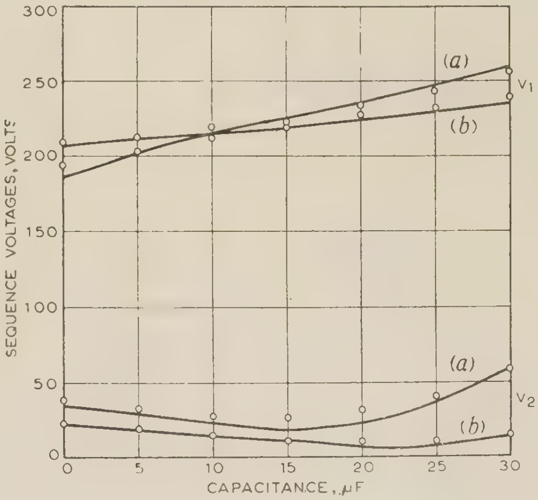

Fig. 4.—Variation of sequence voltages with the capacitance of the phase balancer at full-load speed.

(*a*) Single machine.
(*b*) 2-machine system with one machine as a pilot motor.

Fig. 4 illustrates the effect on the performance of a single machine at 1 460 r.p.m. when the capacitive admittance Y is employed in the manner shown in Fig. 1. For direct comparison, results for the same machine, with the second machine on light-load in parallel as a pilot motor, are included on the

same graph. The agreement between theory and practice is most satisfactory.

The effect of the pilot motor, used with the optimum capacitive admittance, is to make $|V_2/V_1|$ less than 0·04. Thus, the improvement is to diminish the percentage negative-sequence component from 20% for the simple single-phase motor to less than 4% for a 2-machine capacitor-Ferraris–Arno system under optimum conditions—a reduction, that is, in the ratio of 5 : 1. At a given speed, the sequence-component voltages are proportional to their respective sequence-components of current, and the corresponding effect on the negative-sequence currents is therefore a reduction in the same ratio of 5 : 1. Since for the simple single-phase machine the two components of current are equal, the percentage negative sequence component of current in the complete 2-machine system is 20%. This may not represent a high order of symmetry, but in terms of the associated copper loss it is a substantial improvement.

The theoretical result that the same optimum value of capacitance minimizes the negative-sequence components of both voltage and current was verified by direct observations. However, since the minimum is not very pronounced (see Fig. 4, for example) and as it is more important to reduce the negative-sequence current than to secure a precise minimum of the voltage, the preferred method in practice is to use the current bridge and to adjust the capacitance for a minimum reading on the negative-sequence meter.

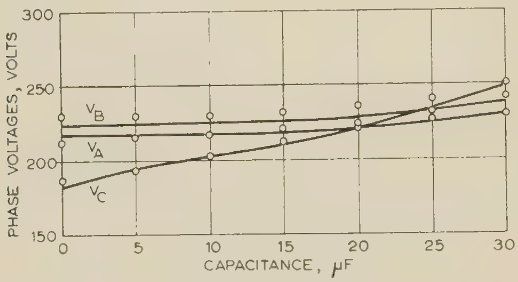

Fig. 5.—Variation of phase voltages with the capacitance of the phase balancer at full-load speed, for a 2-machine system with one machine as a pilot motor.

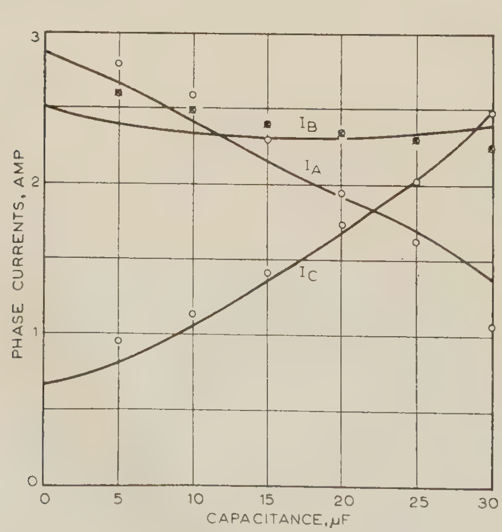

Fig. 6.—Variation of phase currents of the load motor with the capacitance of the phase balancer, at full-load speed for a 2-machine system with one machine as a pilot motor.

Points marked ⊗ correspond to I_B.

Optimum capacitances were found to be 15·0 and 23·0 μF for a simple single-phase machine and the complete 2-machine system, respectively. The corresponding values found by graphical construction were 14·9 and 25 μF, which are in very close agreement. The approximate method, using capacitances corresponding to the imaginary component of the complex admittance ideally required, gives values of 15·5 and 25·5 μF in these two cases. It is clear from the construction described in Section 7.2 that the approximate value is a little larger than the exact value required for minimum negative-sequence component, but that, for the admittances normally encountered in practice, the difference will not be great.

Figs. 5 and 6 show practical results for the phase voltage and current and corresponding theoretical results derived from the sequence components by methods which have been described elsewhere.[5] The theoretical and practical voltage curves are very close and the current curves show the right trends, although the detailed agreement is somewhat less exact.

(4) CONCLUSIONS

The particular manner in which symmetrical-component principles have been employed in the paper is singularly simple and direct and gives theoretical results which are in close agreement with those determined by experiment. To measure the sequence components separately is a natural corollary to the corresponding theoretical principle which treats the sequence components as independent quantities. Moreover, by measuring the sequence quantities directly, the theory can be verified at an early stage in the computation of performance characteristics. Saturation effects are usually negligible, but in any event, when bridge measurements are made under working conditions, non-linearities are taken account of as they occur.

A study of the general Ferraris–Arno system is thought to be desirable as an aid to the proper understanding of the single-phase capacitor motor and its behaviour as a phase convertor, but once it is appreciated that the pilot motor should have as large a current rating as is economically permissible, the design problem is reduced to finding the optimum value of the balancing capacitor to be associated with each load motor. This can be done by a simple geometrical construction, but perhaps the most satisfactory procedure is to determine the approximate capacitance required by the method described in Sections 2.2.3 and 7.2, and then to use the current bridge to give the optimum value quickly and accurately by adjusting for a minimum reading on the negative-sequence meter. The ease and precision with which this can be done can be compared with the difficulty in deducing the correct values from a knowledge of phase quantities (Figs. 5 and 6, for example) which is otherwise the only information available.

It is not, perhaps, premature to observe that the theoretical and practical methods here employed have been applied to a self-propelled combined phase- and frequency-convertor system, and in preliminary tests, near-balance conditions have been achieved over a wide range of frequencies.

(5) ACKNOWLEDGMENTS

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(7) APPENDICES

(7.1) Derivation of Formulae

Applying Kirchhoff's law at the neutral point of the *n*th machine in Fig. 1,

$$I_{An} + I_{Bn} + I_{Cn} = 0 \quad . \quad . \quad . \quad . \quad (22)$$

where $n = p\ (= 1), 2, 3, \ldots N$.

This means that there are no zero-sequence components of current, i.e. $I_{0n} = 0$, and therefore, since the sequence impedances are not zero, there cannot be any zero-sequence components of voltage, i.e.

$$V_{0n} = 0 \text{ and } V_{An} + V_{Bn} + V_{Cn} = 0 \quad . \quad . \quad (23)$$

It is convenient to express the analysis in terms of one machine and the rest. Which of the N machines is singled out for special reference in this way is immaterial, but since there is a distinction in practice between the pilot motor and the load motors, the former is a suitable choice. The pilot motor will be taken to be the first in the series, but will be denoted by the suffix p, rather than 1, for easier identification.

Since the line voltage is common to the complete system, the following relation holds between any pair of machines, but with special reference to the pilot motor:

$$V = V_{Ap} - V_{Bp} = V_{An} - V_{Bn} \quad . \quad . \quad . \quad (24)$$

$$V_{Bp} - V_{Cp} = V_{Bn} - V_{Cn} \quad . \quad . \quad . \quad . \quad (25)$$

Subtracting, and using eqn. (23), it follows that

$$V_{Ap} = V_{An},\ V_{Bp} = V_{Bn} \text{ and } V_{Cp} = V_{Cn} \quad . \quad . \quad (26)$$

and therefore $\quad V_{1p} = V_{1n}$ and $V_{2p} = V_{2n} \quad . \quad . \quad . \quad . \quad (27)$

Thus, corresponding sequence components of voltage are the same for all machines and all the neutral points are therefore at the same potential.

Applying Kirchhoff's law to the junction P,

$$Y(V_{Cp} - V_{Ap}) + \sum_{1}^{N} I_{Cn} = 0 \,. \quad . \quad . \quad . \quad (28)$$

Substituting sequence-component quantities in eqns. (24) and (28) and rearranging,

$$V_{2n} = \frac{V}{3}(1 - a^2) + a^2 V_{1n} \quad . \quad . \quad . \quad . \quad (29)$$

$$Y[(1 - a)V_{1p} + (1 - a^2)V_{2p}] = \sum_{1}^{N} (aY_{1n}V_{1n} + a^2 Y_{2n}V_{2n}) \,. \ (30)$$

Substituting for V_{2n} from eqn. (29) into eqn. (30) and using eqn. (27),

$$V_{1p} = \frac{V}{\sqrt{3}}\,\frac{1 - a}{\sqrt{3}}\,\frac{(1 - a)Y + \sum_{1}^{N} Y_{2n}}{3Y + \sum_{1}^{N} Y_{1n} + \sum_{1}^{N} Y_{2n}} \quad . \quad . \quad (31)$$

Inserting this value of V_{1p} in eqn. (30),

$$V_{2n} = \frac{V}{\sqrt{3}}\,\frac{1 - a^2}{\sqrt{3}}\,\frac{(1 - a^2)Y + \sum_{1}^{N} Y_{2n}}{3Y + \sum_{1}^{N} Y_{1n} + \sum_{1}^{N} Y_{2n}} \quad . \quad . \quad (32)$$

(7.2) Geometrical Construction for the Optimum Balancing Admittance

The expression for the negative-sequence voltage for a single-phase capacitor motor is, from eqn. (13),

$$|V_2| = \left|\frac{V}{3}\right| \left|\frac{Y + \left(\frac{1 - a}{\sqrt{3}}\right)\frac{Y_1}{\sqrt{3}}}{Y + \frac{Y_1 + Y_2}{3}}\right| \quad . \quad . \quad . \quad (33)$$

where, in practice, Y_1 and Y_2 are known complex admittances with positive real parts and negative imaginary components.

Lines OA and OB on Fig. 7 are drawn to scale to represent $-\frac{Y_1}{\sqrt{3}}\frac{1 - a}{\sqrt{3}}$ and $-\frac{Y_1 + Y_2}{3}$, respectively, as shown.

The resistive component of the balancing admittance must be either positive or zero, and Y can therefore be represented by any line OP, provided that P does not fall to the left of the imaginary axis. The lines PA and PB then represent the numerator and denominator, respectively, of the complex fraction in eqn. (33). The condition for minimum negative-sequence component is simply that PA/PB should be as small as possible.

For a given value of $|V_2|$ the ratio PA/PB is fixed. This condition does not determine a unique position for P, but, by a familiar theorem in plane geometry, defines one member of a

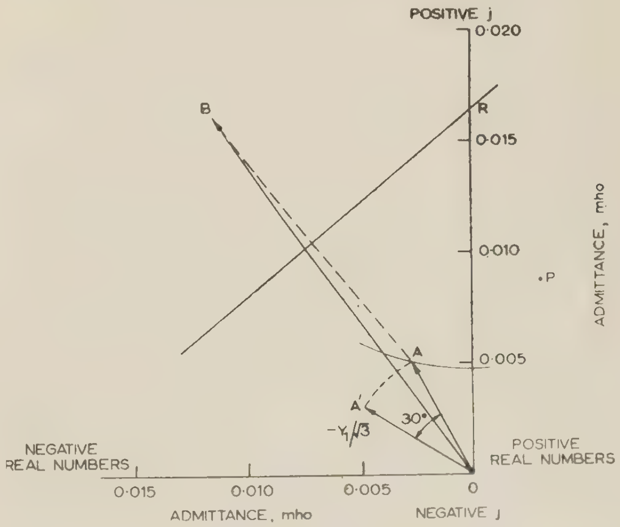

Fig. 7.—Admittance diagram: geometrical construction for finding the optimum value of the balancing capacitor.

Drawn to scale for one machine as a single-phase capacitor motor. $Y_1 = 0{\cdot}0096\backslash\overline{32^\circ}$, $Y_2 = 0{\cdot}05\backslash\overline{58^\circ}$ mhos.

coaxal system of circles which has the fixed points A and B as limiting points. For decreasing values of PA/PB the radii of the circles decrease and their centres approach the point A.

For vanishingly small values of PA/PB, i.e. for $|V_2| = 0$, the circle defined shrinks to the limiting point A, and P therefore coincides with A. Because of the restriction placed on P, however, this is impossible unless A also does not lie to the left of the imaginary axis. It follows that the argument of $-Y_1$ must not exceed 120°, i.e. θ_1, the argument of Y_1, must not be less than 60°—a conclusion which was reached in a different manner in Section 2.2.3.

When $\theta_1 < 60°$, a zero value of $|V_2|$ is impossible and A lies in the second quadrant, as shown in Fig. 7. A minimum value of $|V_2|$ now corresponds to that circle of the coaxal system which just touches the imaginary axis. The point of contact P′ gives the admittance required, and it follows that a pure capacitance is sufficient for both zero and minimum values of negative-sequence component.

Any circle which passes through the two limiting points and has its centre on the radical axis cuts every member of a coaxal system orthogonally. If R is the point where the perpendicular bisector of AB meets the imaginary axis, then RA defines one such circle and the required point P′ is where the arc RA meets the vertical axis.

It will be noticed that OP′ is only a little less than the projection of OA on to the vertical axis, which is the imaginary part of the admittance theoretically required for perfect balance [see eqn. (14)], and it is this which provides the basis for the method for finding the approximate value of Y.

For zero values of Y the point P coincides with the origin, corresponding to a single-phase motor with no provision for balancing.

The same construction can be used for a complete N-machine system if OA is drawn to represent

$$(-)\frac{\sum_{1}^{N} Y_{1n}}{\sqrt{3}}\,\frac{1-a}{\sqrt{3}} \text{ and OB represents } \left(-\frac{1}{3}\right)\sum_{1}^{N} Y_{1n} + \sum_{1}^{N} Y_{2n}$$

DISCUSSION ON
'EARTHING OF LOW- AND MEDIUM-VOLTAGE DISTRIBUTION SYSTEMS AND EQUIPMENT'*

NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 13TH JANUARY, 1958

Mr. A. J. Colgan: I think the author will agree that earthing is a major problem only in rural areas. In urban areas the soil resistivity is relatively low; in fact, there is so much buried metal, such as water pipes, gas pipes and cables, that little difficulty is experienced in obtaining a reasonably good earth at the substation or the consumer's premises. I am not advocating the use of water mains as a means of earthing.

When mentioning methods of earthing other than p.m.e. the author deprecates the use of water mains and dismisses voltage-operated earth-leakage circuit-breakers in one short paragraph. After outlining the relaxations granted to the North Western Electricity Board in connection with the use of p.m.e., the author gives an illustration (Fig. 5) of a small supply to two cottages where he has used p.m.e., and quotes test results. He has used the water main as a means of earthing, and from the tests it is clear that, if the consumers concerned decide in the future—which they might well do—to replace the metal pipes by alkathene or polythene tubing, the earthing system will be ineffective. In fact, if the neutral conductor breaks at B in Fig. 6, and the metal water pipe no longer exists, the cooker frame will acquire mains voltage whether a fault exists on the cooker or not. So his first illustration depends almost entirely on the use of water mains, and I think that this is a typical case where p.m.e. should not have been used.

In the system shown in Fig. 7 the author has again relied upon water mains to acquire an overall resistance within the prescribed limits. What voltage would he expect to find on the frames of the consumers' appliances at Chadderton Heights if the neutral conductor were to break between these premises and Nod Farm?

Bearing in mind the disadvantages of using water mains, I suggest that the author gives further consideration to the more extensive use of continuous earth wires, because if they break the frames of the consumers' appliances are not immediately subjected to what might well be lethal voltages; in any event—as emphasized in the paper—no neutral conductor has broken since p.m.e. was adopted. There is therefore no reason to believe that continuous earth wires would be more liable to breakage, provided, of course, that they were properly erected. It may be that their cost deters the author, but I doubt whether in rural areas, where distributors to small groups of consumers are relatively short, the costs of continuous earth wires would exceed the £4 per consumer which p.m.e. is costing the North Western Electricity Board.

Mr. K. W. Huddart: The discussions have accentuated the importance of continuity of the neutral wire in p.m.e. systems to maintain effective earthing of consumers' installations. In some instances, such as that shown at Sandy Lane Cottages in Figs. 5 and 6, it is possible for the neutral to become discontinuous and for the supply to continue uninterrupted. If a fault then occurs on the line, it is possible, with only single-pole fuses, for the entire fault current to flow through the consumers' relatively light earthing cable, thus causing a fire risk.

What precautions are taken, in a p.m.e. system, to detect a discontinuous neutral, and do they include regular inspection and testing?

Mr. C. H. Morton (*communicated*): Of all the methods of l.v. earthing, p.m.e. is the only one in which danger may result without a prior apparatus fault, and, as is the case with direct earthing using overhead earth wires, a consumer's safety may be jeopardized by events outside his own premises and control. Nevertheless, in practice it appears that the risk with p.m.e. is small, and generally speaking more than one fault is required to cause danger. A particular exception to this is at Chadderton Heights, shown in Fig. 7, where the neutral earth electrode has a resistance of 100 ohms. Thus a broken neutral conductor could

* MATHER, F.: *Proceedings I.E.E.*, Paper No. 2420 S, October, 1957 (see 105 A, p. 97).

cause a substantial rise in voltage between apparatus framework and true earth. If the earth electrode is a little distance away from the premises, no alleviation can be expected from the increase in potential of the building fabric.

The magnitude of the danger to the consumer (or possibly to other consumers) is approximately inversely proportional to the incoming supply voltage; i.e. the highest voltage possible between neutral and earth is equal to the supply-transformer secondary voltage less the incoming voltage to the premises. One possible solution, therefore, in such extreme cases as Chadderton Heights, is to provide an under-voltage release in the live incoming supply which would be electrically held in from the consumer's side of the installation. Such a device could therefore disconnect the supply when the voltage dropped below, say, 200 volts, representing a maximum neutral-to-earth voltage of about 40 volts. Reclosure by the consumer would be necessary, but provided that operation of the device by dips in system voltage was not too frequent, this should be acceptable. Properly designed, such an under-voltage trip should be cheap, reliable and, up to a point, should fail to safety. In any event, it would be a second line of defence only. It would normally be required only in extreme cases, but if used on a more generous scale, it would also protect consumers such as Woodside Farm, which, although still connected to the neutral, could experience relatively high voltages to earth as referred to in Section 19.2(*c*). This latter case could probably be improved, however, by better neutral earthing more easily than could Chadderton Heights.

Mr. F. Mather (*in reply*): Earthing by means of electrodes at substations and consumers' premises is seldom satisfactory, even in urban areas.

With regard to p.m.e. systems, the danger of neutrals breaking should not be exaggerated. The multiple earths form a useful second line of defence which is not a feature of most other earthing systems.

Where private water pipes are used to assist in reducing the overall resistance between neutral and earth, reliance would not be replaced on a single pipe. Any one pipe could be lost without detriment and any appreciable increase in resistance would normally be noticed during the next periodical test.

Continuous earth wires may seem attractive, but they have disadvantages. They are seldom as robust as the neutral conductor, and, if they are increased in section, the cost becomes far higher than that of p.m.e. There is no warning when an earth wire becomes discontinuous, whereas a neutral breakage would probably affect the supply sufficiently to attract attention before any further fault could develop. It is not generally appreciated that unsafe voltages can appear on both sides of a broken earth wire and that the effects can be more serious than those of a break in a p.m.e. neutral.

It has not been found necessary to make regular tests to ensure that neutral conductors are not open-circuited.

Experience has not shown the need for under-voltage releases at consumers' premises, and such a method would have undesirable features.

The remainder of the points raised were dealt with in earlier discussions.

DISCUSSION ON 'ELECTRICITY IN MODERN COMMERCIAL HORTICULTURE'*

Before the South Midland Supply and Utilization Group *at* Birmingham 13*th January, the* Southern Centre *at* Bournemouth 22*nd January, and the* Northern Ireland Centre *at* Belfast 11*th February*, 1958.

Mr. H. J. Gibson (*at Birmingham*): Could the results obtained in a glasshouse be better and more economically achieved in an artificially lighted thermal-insulated building? Perhaps the light intensities required would be difficult to achieve, but I should like the authors' comment on this suggestion.

I agree with them on the importance to the Electricity Boards of the auxiliaries associated with oil- or solid-fuel-fired plants. On the other hand, although direct heating by electricity commends itself, it must be conceded that it does not yet compete economically for commercial purposes with oil and, in a limited number of cases, coal, except for the smaller greenhouse used by the amateur.

Fan heaters seem to have fallen into a certain amount of disrepute, possibly because of the draughts created on plants, and I would ask the authors if my impression is correct. Would they also say that, if the fan heaters are placed near the ground, the effect of draughts on the top parts of the plants could be entirely eliminated?

I am less pessimistic than the authors, and consider that there is still a future for soil warming, particularly for the busy practical man who does not have the facilities to procure all the special conditions necessary for ideal plant growth for his commercial activities. I am sure that the technique will have substantial application in due course.

With reference to mist propagation, would the authors confirm that the soil warming used for this method of watering is about 13–15 watts/ft^2 and not, as I thought, about 25 watts/ft^2? Would it be possible to achieve the same results with mist propagation using storage heat? This would mean a substantially heavier load and consequently a higher surface temperature of the bed. Do the authors think the higher surface temperature would have a detrimental effect on the roots of the plants?

There is little mention of air conditioning, although I should imagine that, particularly in urban areas, it would be a great boon to the horticulturist. I believe it is extensively used in America, both for cooling in the summer and for conditioning and heating in the winter, and perhaps the authors could tell us more about this application.

Floor warming might perhaps have been more efficient and have given better comfort conditions for workers in the potting shed, but for existing sheds the overhead infra-red heaters seem to be satisfactory.

Mr. L. Arkinstall (*at Birmingham*): It is evident from the paper that small-scale amateur greenhouse experiments can sometimes be developed for commercial purposes, and I suggest that the Midlands Electricity Board's experiments at Wombourne, to convert greenhouse heating to an off-peak load, will also be useful in this respect. The Wombourne experiments have included the heating of a 20 ft × 10 ft greenhouse by heat storage in the central

* Cameron Brown, C. A., and Gray, A. W.: *Proceedings I.E.E.*, Paper No. 2272 U, January, 1957 (see 104 A, p. 249).

concrete path. The heating elements comprise mains-voltage copper-sheathed mineral-insulated heating cables, solidly embedded 2 in below the surface of the 8 in thick concrete path, with supply intake restricted to the off-peak hours of 7 p.m.–7 a.m. and 1 p.m.–3 p.m. each day. The surprising fact is that, even if the electricity supply were not restricted, the system would require intake only during these off-peak hours when operating at a temperature of 45° F. A feature of the system is the accurately maintained night temperature, coupled with the economy due to the self-regulating characteristics of the low-temperature heated concrete in relation to the solar heat gain. The system also provides a valuable factor of safety during possible supply failures.

Many football clubs are already using floodlighting: could they not make use of their supply capacity for turf heating?

Do the authors consider that off-peak techniques are practicable for mist propagation, in view of the required root temperature of 90° F, and could they suggest suitable loadings?

Mr. J. H. Addenbrooke (*at Birmingham*): Does the use of overhead infra-red heaters to warm the men at the potting benches have any effect on the plants? I would have thought that the plants would be in a delicate state when they are potted, and that the intense overhead heat would harm them.

Mr. T. D. G. Wintle (*at Birmingham*): I should like more information on the authors' experience with control equipment and switchgear, plugs and sockets, and on the maintenance which is required to keep them in reasonable condition in greenhouses. Those installations which I have seen—largely, I admit, in the amateur class—have not been well carried out and have been in a bad state of repair. I understand from the paper that quite a large amount of low-voltage equipment is used: is there any trouble from joints on the low-voltage side?

Regarding the failure of supply, I should imagine that there is an equal if not greater risk of a heating system failing due to bad contacts in switches or joints, particularly in thermostats. Can the authors give further information on this?

If it is intended to run ½ in of water over everything, obviously fully watertight fittings, i.e. immersion proof, would have to be used. I assume that we have had experience in this country with similar conditions, and I should welcome more information from the maintenance aspect.

Mr. F. H. Lealand (*at Birmingham*): Is the suspended humidifying unit used with mist propagation in a greenhouse a proprietary article or a made-up one?

Although humidity control is probably not so critical as for some industrial applications, fairly close control is no doubt needed to avoid over-saturation, and I should like to know how this is achieved.

Mr. M. C. W. Gould (*at Bournemouth*): A year or two ago a greenhouse was exhibited at the E.R.A., Shinfield, showing among other things automatic shading, and I wonder whether there has been any further development on the ideas then shown.

Secondly, I should like some further information on the light treatment of St. Paulia. I understand that warm white fluorescent tubes are normally used, but would like details of mounting heights, spacing, temperatures, etc.

I have recently visited a few of the potato lighting installations in this area, and during a recent warm spell the temperature inside the store was well above 50°. Since the ambient temperature was even higher, it was impossible to reduce considerably the inside temperature by means of the fans fitted. The more recent cold weather has certainly helped, but the authors' comments would be of interest.

There has been some hesitation in the installation of light irradiation for assisting the growth of tomatoes. Some of the difficulties which we experienced in using high-pressure mercury-vapour lamps on tomatoes were perhaps due to the fact that many large-scale growers use part of their main growing house for propagating purposes and the temperature therefore tends to be rather higher than when a separate propagating house is used. Moreover, the lamps themselves will increase the temperature by a few degrees. I wonder whether the authors have had any further experience in this line.

I feel that the selection of the customer is of equal importance to, if not of greater importance than, the selection of the equipment, and this particularly applies to the grower who has not a guaranteed market.

Mr. F. Snaith (*at Bournemouth*): Is there any advantage to be gained by using warm water for watering plants, e.g. to soil-warm the gravel used in ring culture?

Mr. A. W. Cross (*at Bournemouth*): Has any progress been made in hydroponics, for I understood in 1940 that it had a reasonable commercial future?

Mr. H. P. McKeown (*at Belfast*): Reference is made in Section 2.1.1 to e.l.v. transformer-fed bare wires as the ideal for amateurs, but surely chemical action of fertilizers, etc., in the soil would cause progressive corrosion, resulting in reduction of cross-section of the wires and therefore of loading? Could the authors give any further information regarding the extent of such corrosion and its likely effect on loading over a period of years?

In the case of frame heating by 240-volt cable, if the same type of cable is used for soil warming and air heating, is the surface temperature of that part of the cable in air not liable to rise to an undesirable value?

The distribution of insecticides and fungicides in the form of an aerosol mist sounds an attractive alternative to continual spraying throughout a growing season, but can this method be relied upon to ensure adequate deposition of the mist on both upper and lower surfaces of leaves in all parts of the house?

From the purely horticultural aspect the delaying of the flowering of the chrysanthemums by controlling the amount of light electrically seems hardly worth while when the same effect could doubtless be obtained by the judicious timing of the rooting of cuttings.

Messrs. C. A. Cameron Brown and **A. W. Gray** (*in reply*): To conserve space we propose to reply to speakers individually rather than by subject.

Mr. Gibson.—We are not pessimistic about the future of soil warming and are actively encouraging its use, particularly in mist propagation beds; the use of storage heating for this purpose certainly deserves to be investigated. There is a place for fan-unit heaters in glasshouse heating, but there are various complications in their use. Air-conditioning sounds attractive, but at present the cost of equipment would seem to be quite uneconomic.

Mr. Arkinstall.—The Midlands Electricity Board work on off-peak space heating is valuable, and we look forward to further accounts from them and from the E.R.A. Soil warming of football pitches is now coming into being, and is being made easier to apply because of the existence of floodlighting.

Mr. Addenbrooke.—The infra-red heaters used to warm the men at the potting bench do not appear to have any adverse effect on the plants, owing to the very short time they are subjected to the infra-red rays.

Mr. Wintle.—We appreciate the necessity for using the correct type of control-gear and equipment in greenhouses and glasshouses, and where the correct equipment is properly installed, such methods are completely satisfactory.

Mr. Lealand.—The 'artificial leaf' controlling the misting operation is a proprietary article and operates, not on air humidity, but on the resistances offered by the water path between two embedded electrodes.

Mr. Gould.—While further investigations on the use of automatic shading by running coloured water over the greenhouse are still being carried out, there is no further progress to report at this date.

General experience from potato lighting installations emphasizes the benefits to be obtained from this method of storage and controlled sprouting. When the ambient temperature is high there is no doubt that continued air circulation from the fans does much to mitigate the difficult conditions. It is agreed that, where results from supplementary lighting for tomato seedlings have been disappointing, the usual cause is lack of temperature control in the propagating houses and failure to allow for the temperature rise under the lamps. The amount of benefit obtained is, however, in direct proportion to the grower's skill.

Mr. Snaith.—While it may be an advantage to warm the water for general watering for ring culture, it is very doubtful whether this would be a paying proposition or whether the benefits would be sufficient to offset the additional cost.

Mr. Cross.—Excellent results are still being obtained from the use of hydroponics. It is not, however, a practice which has taken on very well in this country, although we believe it is much more widely used in America.

Mr. McKeown.—Corrosion of low-voltage warming wires does happen, but can now be prevented by using plastic coverings. There is no undue rise of temperature when soil-warming cables run in air, although the mineral-insulated type can damage leaves in contact with them. Timing of the rooting of chrysanthemum cuttings has little or no effect on the time of flowering.

DISCUSSION ON 'THE MEASUREMENT OF EARTH-LOOP RESISTANCE'*

Before the WEST WALES SUB-CENTRE *at* SWANSEA 14*th November, and the* NORTH LANCASHIRE SUB-CENTRE *at* BLACKBURN 11*th December*, 1957

Mr. C. G. Richards (*at Swansea*): I feel that those responsible for the 13th Edition of The Institution's Wiring Regulations intended their diagram to illustrate in principle a simple testing equipment only, and improvements embodying rectifiers and other refinements have been designed. Mains-operated sets using rectifiers appear to correct some of the errors due to inductances. I agree that the independent-generator testing set with its reversing commutators provides greater accuracy than other commercial sets, and such as are required in present-day installation practice and testing. Accurate results are necessary, particularly on older underground systems designed for electric lighting only, but now still in service for many other uses of electricity. Testing for earth continuity and neutral earthing are of importance for installations supplied from overhead systems, especially in rural areas.

Mains earth-continuity testing sets developed from the 13th Edition fundamental machine to eliminate certain errors in earth-loop testing, i.e. those due to inductances, were intended as reasonably low-cost instruments. However, while the independent-generator machine is probably more expensive to purchase than the mains-operated tester, for earth-resistance testing it is not only more accurate and better than the alternatives but will save its purchase price in each year of use, on the present-day costs of testing labour of various grades at 6s.–12s. 6d. per hour, including transport and on-costs. The types of testing machine best suited to use by installation inspectors and/or test engineers, apart from the lowest overall cost offered by the independent-generator type, has also to be considered from the supply-availability aspect. This is an important factor in the cost of installation inspectors' time on new housing estates, where complete installation testing may need to be concluded in many houses before the new supplies can be commissioned.

Occasionally there is a case for the over-current method, but as a general principle I feel that the author has established his case in favour of the hand-operated instrument. Heavy testing currents passed through the earth path could cause defects in certain classes of metallic bonding devices in house wiring, without their subsequent proper detection. However, if the installation is first tested by the equipment advocated in the paper, with low currents, some prototype over-current testing of various installations could be justified, since the information yielded would give satisfaction.

Mr. J. Sumner (*at Blackburn*): The Summary refers to the accuracy of earth-loop tests, but it should be noted that factors other than methods of test are involved. For instance, if there is an earth fault on the neutral conductor, either on the supply cable or on a consumer's installation, the results obtained will be affected. With a low-resistance fault on the neutral the instrument would give values relating to the fault resistance and not the earth-loop impedance or resistance. When these faults are present, instruments of all the types now on the market may indicate that conditions are satisfactory when the earth electrode at the substation has a resistance considerably higher than that required according to the Electricity Supply Regulations.

Section 2 states that, although there is some inductance in the earth loop under normal circumstances, this can be neglected. This is contrary to the inferences in the Summary, which appears to indicate that accuracy in the results is of prime importance.

What is the range of frequency over which the reversed d.c. instrument is inaccurate, on the assumption that the supply frequency is 50 c/s? A considerable number of tests have been carried out locally with ohmmeters, loop-impedance testers and with the instrument designed by Mr. Roscoe, and under most circumstances there is little disagreement between them. In my opinion, variations up to 50% would not seriously affect the conclusions arrived at in many tests. When considering this particular problem, the points where difficulties are likely to occur are either due to a high resistance at the substation earth electrode or the consumer's earth electrode. When both are satisfactory, the test results will probably be satisfactory. The person operating instruments of this type should be conversant with the possibility of a fault on the neutral, and some knowledge of the values likely to be obtained should have been gained from experience on previous jobs.

Loop-impedance tests are usually undertaken in order to ascertain whether the protective devices will operate when a fault occurs, and provided that this point is covered, precise values are not important. There is a suggestion in the paper that the Roscoe tester would not show whether there are any bad contacts such as films in the circuit, but this method involves higher

* TAGG, G. F.: *Proceedings I.E.E.*, Paper No. 2165 M, September, 1956 (see 104 A, p. 215).

currents than other tests, and films should consequently have little or no effect on the results.

Mr. F. Robinson (*at Blackburn*): Does the author agree that there is nothing to be gained by measuring the earth-loop impedance if the consumer's loading is within the range of an available Roscoe instrument? The Roscoe instrument gives a definite indication of whether a fuse within the 15–60 amp range will rupture in the event of an earth leakage. A positive indication is proof that a fault current at least twice as large as the selected fuse rating has actually passed through the earth circuit. This to me is far more satisfactory than finding that the earth-loop resistance is 2 ohms and so should pass a current of 120 amp.

Should the instrument give a negative indication, knowledge of the earth-loop impedance would not indicate the location of the high impedance. Earth-resistance tests would have to be taken on the consumer's, and probably also on the supply-sub-station, earth electrodes. It will be found that either or both these will have a resistance higher than regulations permit. An attempt should then be made to bring the earth-electrode resistance within the regulation limits. If, as sometimes happens, this is not possible, owing to the nature of the ground in the vicinity of the electrodes, an alternative method of earth protection must be used, such as p.m.e. fifth-wire or an earth-leakage circuit-breaker on the consumer's premises. The latter would give protection if the substation earth-electrode resistance were not more than four times that of the consumer's earth electrode. Earth-leakage circuit-breakers should not be used if either of the alternatives can be applied, since they add further complications and sometimes become mechanically defective.

The Roscoe instrument has a range which enables a suitable earth-resistance test to be carried out on the premises of domestic, farm, small commercial and industrial consumers.

Large industrial consumers' installations are earthed to the supply-substation earth electrode, which is on their premises, and the earth-loop resistance can be measured by a continuity tester. A further group of industrial and commercial consumers take loads of 40–200 kW and do not always have the supply substation on their premises. This group are outside the range of the present Roscoe instrument, and so earth-loop measurement must be taken. I hope that an instrument of the Roscoe type will be made available for testing the earth circuit of consumers in this group.

Dr. G. F. Tagg (*in reply*): The advantages of the hand-driven generator set are its accuracy and its ability to carry out a test whether a supply is available or not. If a test is made with such an instrument on a circuit containing a source of 50 c/s voltage, and the instrument is run at 50 c/s, the pointer will move erratically about the scale, and by speeding up the instrument, thereby increasing the frequency to, say, 55 c/s, the effect is eliminated and the instrument will give a steady reading.

The question of neutral faults has been raised on a number of occasions and it is sufficient to say that the test is of little value if such faults are present. This is not the fault of the instruments but of the method suggested.

The question of films has been discussed before. The fact that a circuit will carry a heavy current at the moment a test is made is not necessarily a guarantee that it will do so at all times in the future. The idea behind the test first with low current, then with high, and finally with low current again is that it is often possible to detect conditions which may become troublesome at a later date. This test is not, of course, infallible, but it is likely to be of more use than that which consists of the passing of a heavy current only.

Inductance in the circuit does cause the impedance to be greater than the resistance, but except in such cases as a factory with its own substation, where the earth-continuity conductor may consist entirely of steel conduit, this difference is not likely to be serious. In most cases there is already a considerable amount of resistance in the circuit.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, OCTOBER 1958

CONTENTS

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Example.—SMITH, J.: "Overhead Transmission Systems', *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

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